NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

SYSTEMS ENGINEERING CAPSTONE PROJECT REPORT

EVALUATION OF THE OPERATIONAL BENEFITS VERSUS COSTS OF AN AUTOMATED CARGO MOVER

by

Team ACME
Cohort 311-152P

December 2016

Project Advisor: Gregory Miller

Approved for public release. Distribution is unlimited.

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.			
1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** December 2016	**3. REPORT TYPE AND DATES COVERED** Capstone project report	
4. TITLE AND SUBTITLE EVALUATION OF THE OPERATIONAL BENEFITS VERSUS COSTS OF AN AUTOMATED CARGO MOVER			**5. FUNDING NUMBERS**
6. AUTHOR(S) Team ACME, Systems Engineering Cohort 311-152P			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number ____N/A____.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.			**12b. DISTRIBUTION CODE**

13. ABSTRACT (maximum 200 words)

This report examines the use of an automated robotic pallet mover during resupply missions in support of forward-deployed Marine units. The pallet mover is capable of loading and unloading itself and its cargo from MV-22 and CH-53 aircraft, and subsequently transporting that cargo 3,281 feet over unimproved terrain. The report explores the operationally relevant scenarios where a robotic pallet mover could be used, to determine whether it is beneficial. The scenarios are used to quantify the different performance measures using the pallet mover compared to traditional methods of working parties composed of available Marines and material handling equipment such as forklifts. The robotic pallet mover's logistics footprint and life-cycle cost are presented as part of this report. Analysis of modeling and simulation results identified statistically significant differences between the three methods (robotic pallet mover, working parties, material handling equipment) for loading and unloading, and impacts to logistical footprints, number of sorties, and cost. The benefit of the eXpeditionary Robo-Pallet is in its ability to quickly embark and debark from aircraft, reducing the time aircraft spend on the ground waiting for cargo to be loaded or unloaded. This report recommends additional investigation of other potential benefits or drawbacks.

14. SUBJECT TERMS autonomous cargo mover, cost analysis, operational logistics, life-cycle cost, modeling and simulation, unmanned cargo mover, resupply, EFSS, MV-22, CH-53, XRP			**15. NUMBER OF PAGES** 143
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release. Distribution is unlimited.

EVALUATION OF THE OPERATIONAL BENEFITS VERSUS COSTS OF AN AUTOMATED CARGO MOVER

Team ACME, Systems Engineering Cohort 311-152P

Joshua Culp
Jon Feeney
Cleevens Meus
Joshua Davis
Jennifer Kays
Jesse Sumner
Richard Domondon
Adam Martin

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
December 2016

Lead editors: Joshua Davis and Jon Feeney

Reviewed by:
Gregory Miller
Project Advisor

Accepted by:
Ronald Giachetti
Chair, Systems Engineering Department

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

This report examines the use of an automated robotic pallet mover during resupply missions in support of forward-deployed Marine units. The pallet mover is capable of loading and unloading itself and its cargo from MV-22 and CH-53 aircraft, and subsequently transporting that cargo 3,281 feet over unimproved terrain. The report explores the operationally relevant scenarios where a robotic pallet mover could be used, to determine whether it is beneficial. The scenarios are used to quantify the different performance measures using the pallet mover compared to traditional methods of working parties composed of available Marines and material handling equipment such as forklifts. The robotic pallet mover's logistics footprint and life-cycle cost are presented as part of this report. Analysis of modeling and simulation results identified statistically significant differences between the three methods (robotic pallet mover, working parties, material handling equipment) for loading and unloading, and impacts to logistical footprints, number of sorties, and cost. The benefit of the eXpeditionary Robo-Pallet is in its ability to quickly embark and debark from aircraft, reducing the time aircraft spend on the ground waiting for cargo to be loaded or unloaded. This report recommends additional investigation of other potential benefits or drawbacks.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF FIGURES

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF ACRONYMS AND ABBREVIATIONS

AoA	analysis of alternatives
APUC	average procurement unit cost
AT	ammunition trailer
ATP	ammunition transfer point
CBS	cost breakdown structure
CDR	critical design review
CER	cost estimating relationship
CLS	contractor logistics support
CONOPS	concept of operations
DLA	Defense Logistics Agency
dMan	Dexterous Manipulation System
DOD	Department of Defense
EFSS	Expeditionary Fire Support System
FARP	forward arming and refueling points
FR	federal research
FSS	Fire Support Systems
FTE	full time equivalent
GERM	general error regression method
KPP	key performance parameter
KSA	key systems attribute
LIDAR	Light Imaging, Detection, and Ranging
LS3	Legged Squad Support System
LSV	Light Strike Vehicle
MAGTF	Marine Air Ground Task Force
MCSC	Marine Corps Systems Command
MCTSSA	Marine Corps Tactical System Support Activity
MEU	Marine Expeditionary Unit
MHE	material handling equipment
NCCA	Naval Center for Cost Analysis
O&S	operations and support

P&D	production and delivery
PdM	Product Manager
PHS&T	packaging handling storage and transportation
PM-T	prime mover - trailer
R&D	research and development
RIF	Rapid Innovation Funding
SBIR	Small Business Innovation Research
SIAT	Systems Engineering, Interoperability, Architectures & Technology
SMSS	Squad Mission Support System
TPM	total productive maintenance
TRL	technology readiness level
TTP	tactics techniques and procedures
USMC	United States Marine Corps
XRP	eXpeditionary Robo-Pallet

EXECUTIVE SUMMARY

The Marine Corps operates as a Marine Air Ground Task Force, often organized as a Marine Expeditionary Unit (MEU). According to the "Marine Corps' Expeditionary Force 21," these mobile units are "optimized to be expeditionary" to ensure they can reach a "crisis quickly." One of the many components of a MEU is an Expeditionary Fire Support System (EFSS) that provides close-in fire support to the operating forces. When an EFSS team needs administrative or combat resupply, one of four CH-53K Super Stallion aircraft (rotary wing aircraft) or one of 12 MV-22B Osprey aircraft (tilt-rotor aircraft) assigned to the MEU is tasked with delivering the provisions. The only current methods of loading and unloading these two types of aircraft are by using material handling equipment (MHE) or manually, by forming a working party of the available Marines to carry the cargo on or off of the aircraft. MHE is often not available and a working party takes Marines away from their primary duties. Marine Corps Systems Command (MCSC) is exploring the use of an expeditionary robotic pallet mover (XRP) as a supplement to working parties and MHE. It is currently under development by Stratom Inc. through a Rapid Innovation Funding (RIF) effort. However, there is no data regarding their quantified benefit versus their cost or logistics footprint.

This report examines the use of XRPs to move resupply cargo over unimproved terrain to and from an MV-22 and CH-53. The report provides quantified results to inform near-term decisions which the Product Manager for Fire Support Systems makes as he transitions this technology from a RIF effort into a program of record. Given the modeling and simulation results alone, the XRP has an advantage in all scenarios with the exception of unloading an MV-22, where MHE proves faster. Life-cycle costs for a fleet of 100 XRPs are estimated to be $78M. This cost includes research and development, production and delivery, operations and sustainment, and disposal.

The problem space is explored by first studying the results of a stakeholder analysis. These results provide a better understanding of how the XRP must operate and of the system requirements. The main stakeholders described are the XRP programmatic decision makers and the XRP operators and maintainers. Stakeholder needs analysis

resulted in several key findings which include the requirement to decrease load and unload times by 10% while not significantly increasing the maintenance burden on operators. The problem space is further explored by studying the tactics, techniques, and procedures (TTPs) associated with resupplying an EFSS unit. There will be a need to make some minor revisions to existing TTP, mostly with regard to the safe use of a semi-autonomous vehicle. The report emphasizes the importance of how the XRP interfaces with other fielded systems, specifically those interfaces dealing with dimensions, weight, battery, and fuel constraints where a noncompliance precludes transport on the MV-22, CH-53, as well as other Naval assets.

Next, the report provides a review of the XRP requirements. The review looks for the requirements outlined in the Critical Design Review to be correct, feasible, unambiguous, and verifiable. It also identifies additional requirements pulled from the stakeholder and TTP analysis. Existing requirements for weight, physical dimensions, speed, and carrying capacity are found to be valid. Specific operational requirements for reducing load and unload times were added. Finally, recommendations are provided to improve the wording of several ambiguous or conflicting requirements.

The modeling and simulation effort required the creation of a computational model in Imagine That Inc.'s ExtendSim, a commercial discrete-event modeling software package. The model simulated the preparation, loading, securing, and subsequent unloading of cargo on both types of aircraft. The modelers varied durations for each step based on the known and estimated differences in timing for each method: MHE, working party, and XRP. This required simulation of 12 variants: loading and unloading of two aircraft, using three different handling methods. The number of pallets and number of aircraft were kept constant across the scenarios. The output measures were the total duration for each load and unload operation. The modelers performed post-simulation analysis to evaluate manpower and aircraft utilization impacts. Monte Carlo simulation and subsequent statistical analysis indicated the XRP outperforms working parties by an average of 225 minutes and outperforms MHE by four minutes to load two tons of cargo when using the MV-22. When using the CH-53, load time for the XRP is 645 minutes faster than using a working party and 72 minutes faster than using MHE to load five tons of cargo. When performing unloading operations using the MV-22, the XRP outperforms working parties by an average of 210 minutes and MHE outperforms the XRP by 18 minutes to unload two tons of cargo. When using the CH-53, the XRP outperforms working parties by an average of 580 minutes and MHE by five minutes to unload five tons of cargo. The benefits of the XRP are clearly shown when the amount of cargo that needs to be transported is reduced or when time spent manually moving cargo at a landing zone is not ideal. However, these benefits come at a cost. Since the aircraft have weight carrying limits, transporting the weight of the XRP means less resupply cargo can be transported. In order to deliver the same amount of resupply cargo, more sorties will have to be flown. Therefore, the tradeoff of the XRP becomes more difficult when factoring the cost of flight hours for the aircraft transporting cargo due to the additional sorties required to transport the cargo load.

Next, the report outlines and defines the life cycle logistics requirements for the XRP. The report uses Stratom's subsystem decomposition to support an analysis of anticipated preventive and corrective maintenance actions. The report explicitly addresses the logistics requirements in terms of the three levels of maintenance defined by the Marine Corps as (1) organizational, (2) intermediate, and (3) depot. For example, changing the engine oil and oil filter is an organizational-level activity, while welding a cracked frame is a depot activity. Additionally, the seven elements of support infrastructure that pertain directly to the maintenance of the XRP are explored: supply support; test, measurement and handling; maintenance facilities; maintenance and support personnel; training; packaging, handling, storage and transportation; and software resources.

The report then provides a life-cycle cost estimate. A tailored cost breakdown structure with four phases (research and development cost, production and delivery cost, operation and support cost, and disposal cost) is presented. The cost model is described, along with its assumptions, limitations, and data sources. For example, the average procurement unit cost of the XRP was $379,000. This figure was found through a cost estimating relationship equation based on cargo carrying weight of four similar Department of Defense systems. As part of operations and support, training costs are based on an estimate for the duration of a single operator course multiplied by annual student throughput and multiplied by the expected life span. The operations and support costs include all elements of support infrastructure defined previously.

This report concludes that the XRP can save an average of 210 minutes unloading the MV-22 and 580 minutes unloading the CH-53 over the use of a working party. The tradeoffs are a reduced load per sortie and increased logistics burden and costs. Experience with the units fielded via the RIF can validate the modeling and simulation results, information on logistics impact, and system requirements described in this report. A thorough understanding of cost versus benefit is necessary before transitioning to a formal program of record.

I. INTRODUCTION

A. BACKGROUND

The Marine Corps operates as a Marine Air Ground Task Force (MAGTF), often organized as a Marine Expeditionary Unit (MEU). At any given time, there are three MEUs afloat around the world, enabling the Marines to respond to a crisis in a six-hour window (Wade 2016; Worley 2006). These mobile units are “optimized to be expeditionary” to ensure they can reach a “crisis quickly” (United States Marine Corps 2014a, 5). As an amphibious force, the MEU is uniquely able to operate in the littoral region (land area within 200 miles of the shore) (United States Marine Corps 2014a). Figure 1 illustrates the composition of a typical MEU and Amphibious Ready Group. Included in this group are various aircraft, ships, amphibious vehicles, land vehicles, and other materials. One of the many components of a MEU is an Expeditionary Fire Support System (EFSS), manned by five Marines (United States Marine Corps 2013). The EFSS is a fire support unit that is “lighter, more mobile and vertically transportable for missions requiring tactical versatility, speed and close-in fire support” to the operating forces (General Dynamics 2016). In Figure 1, depicted inside the gray box, are the eight vehicles that compose the EFSS. Four of the vehicles tow the rifled 120 mm mortar used in fire support missions. As seen in Figure 2, the tow vehicle is Light Strike Vehicle (LSV) and each can carry up to four Marines. The remaining four vehicles carry administrative and combat supplies (including ammunition) (Mizokami 2016). The supply vehicles are also LSVs. Figure 2 also depicts the towed 120 mm rifled mortar and the mortar rounds, the prime mover–trailer (PM-T) and the ammunition trailer (AT) components of the EFSS. When an EFSS team needs administrative or combat resupply, one of four CH-53K Super Stallion aircraft (rotary wing aircraft seen in the orange box in Figure 1) or one of twelve MV-22B Osprey aircraft (tilt-rotor aircraft seen in the blue box in Figure 1) assigned to the MEU is tasked with delivering the provisions.

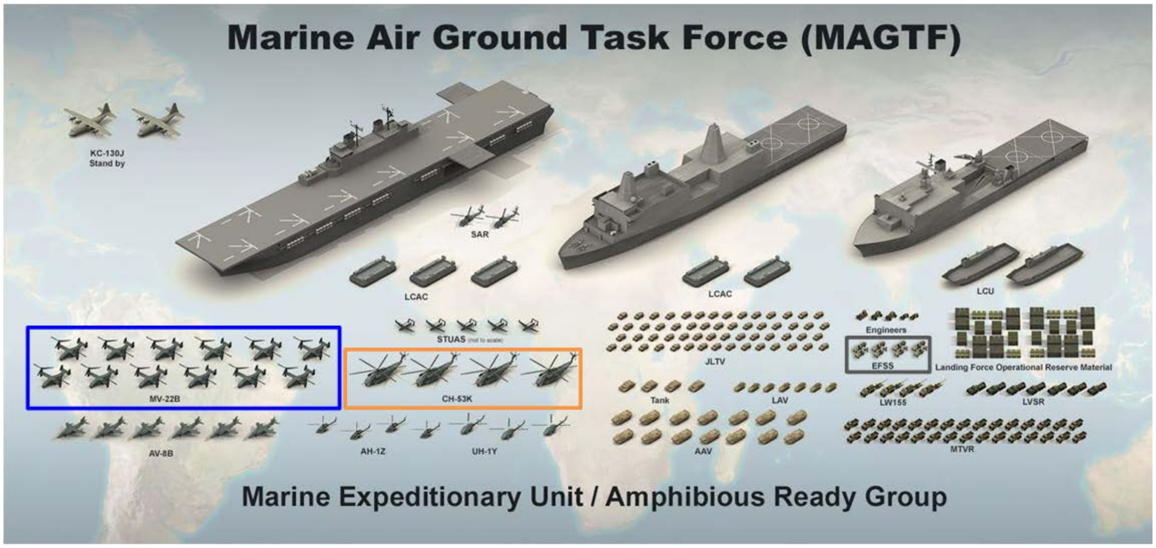

Figure 1. MAGTF Vehicles and Aircraft. Source: Mizokami (2016).

Figure 2. Expeditionary Fire Support System. Source: General Dynamics (2016).

The only current methods of loading and unloading these two types of aircraft are by using material handling equipment (MHE), or manually by forming a working party of the available Marines to carry the cargo on or off of the aircraft. Figure 3 depicts Marines moving cargo using a forklift, which is an example of MHE. Depicted in Figure 4 is the manual method of cargo moving, a working party of Marines. Due to the amphibious and expeditionary nature of most Marine Corps missions, MHE is often not available at the expeditionary airfields, forward arming and refueling points (FARP), and landing zones where United States Marine Corps (USMC) rotary wing and tilt-rotor aircraft operate. Even when MHE is available, the numbers are severely limited, causing undue delays in loading and unloading cargo from aircraft. These delays force the aircraft to shut down and wait, or wait on the ship deck, airfield, FARP, or landing zone with engines running while burning costly fuel, and accruing costly aircraft hours. In non-permissive environments, these delays also increase the risk of exposure to enemy actions. There are also situations when cargo which could be carried internally must be carried externally as a slung load beneath the aircraft due to the lack of MHE to load it aboard the aircraft at remote and austere landing zones—especially when the cargo is too heavy for Marines to lift and load aboard the aircraft manually. Slung loads create greater inherent risks to personnel, airframes, as well as create greater risks due to enemy actions. The Marine Corps is a small, fast, light, amphibious and expeditionary force. Spare Marines are not available to sit idly by and wait for aircraft to arrive so that they can load and unload them. Any time a working party is formed to manually load or unload aircraft, those Marines are being taken away from their primary duties.

Figure 3. MHE Moving Cargo. Source: Stratom Inc. (2016).

Figure 4. Working Party Moving Cargo. Source: Stratom Inc. (2016).

The Marine Corps is exploring a solution to load and unload MV-22 and CH-53 aircraft in austere environments without the requirement for MHE to be present, and with a potential reduction in time and manpower over the current capabilities (Stratom 2015). The Marine Corps is currently addressing this need through a Small Business Innovation Research (SBIR) effort that has transitioned to a Rapid Innovation Funding (RIF) effort. A contract has been awarded to Stratom Inc. in Boulder, CO in order to develop a "self-propelled robotic pallet system capable of transporting supplies or ammunition from a MV-22 and CH-53 over unimproved terrain using tele-operative or waypoint control from a handheld control unit" (Stratom 2015, 4). The end goal of this RIF effort is a production-ready robotic pallet mover at technology readiness level 7 (TRL 7) (Stratom 2015). Figure 5 is a sketch of a production robotic pallet mover.

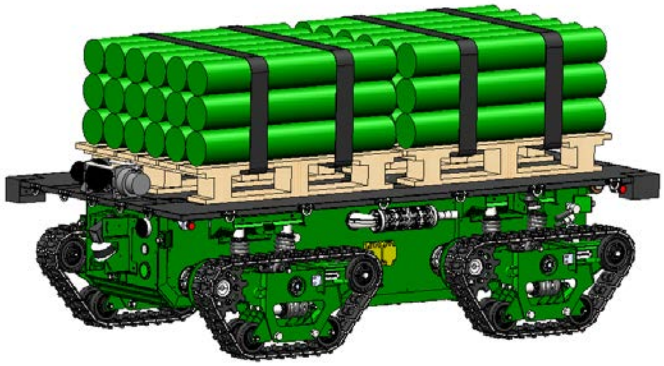

Figure 5. Robotic Pallet Mover. Source: Stratom Inc. (2016).

B. PROBLEM STATEMENT

The robotic pallet mover technology is potentially beneficial across several communities and units in the Marine Corps including the resupply of infantry units, delivery of aircraft maintenance parts to flying squadrons who are forward deployed, and humanitarian assistance/disaster relief operations. This development is funded by the RIF effort to transition this technology for the resupply of EFSS units (Stratom 2015). An EFSS is a towed and rifled 120 mm mortar, which is internally transportable via MV-22, as shown in Figure 6, and CH-53 (United States Marine Corps 2013, pp. E-6). Operationally deployed EFSS units require regular resupply of water, food, mortar rounds, small arms ammunition, fuel, batteries, and other items as required, such as repair parts. The RIF effort to mature the robotic pallet mover technology and transition it to the Fleet Marine Force is managed by the Product Manager for Fire Support Systems (PdM FSS) within Marine Corps Systems Command (MCSC). The contractor developing the robotic pallet mover, Stratom Inc., provided the PdM with a report summarizing the benefits and potential cost of the system (Stratom 2015). It was unknown if the report was complete and accurate. The problem this project addressed was that the PdM had no independent assessment of the system’s real performance potential, cost or logistics footprint on which to make programmatic acquisition decisions.

Figure 6. Loading an EFSS aboard an MV-22 Osprey. Source: www.MilitaryMashUp.com (2016).

C. GOALS AND OBJECTIVES

The objective of this project was to perform modeling and simulation, and a life-cycle cost analysis, of the robotic pallet mover in a variety of operationally relevant scenarios to quantify the potential benefits and impacts to the Marine Corps, and specifically for the EFSS program office. The goal was that these quantified results serve as input to inform near-term decisions which the PdM FSS must make as he works to transition this technology from a RIF effort into a program of record. The PdM FSS will be required to submit Program Objective Memorandum requests for future funding to procure, test, field, and maintain the robotic pallet mover system. The results of this modeling and simulation effort also served to inform the PdM FSS in his development of a nominal mission profile to affect the generation of a relevant and testable performance specification and approved acquisition objective, which is the number of systems required to fulfill the mission need. This modeling and simulation, and cost analysis effort investigated the potential utility, and benefit of the robotic pallet mover technology within a MEU-sized MAGTF. The analysis focused on expeditionary airfields, FARP sites, austere landing zones, and use on the flight deck of U.S. Navy amphibious ships. Larger scenarios, such as use at aerial ports of embarkation, were not considered in this report. The results of this effort also served to inform PdM FSS of which scenarios benefited from the robotic pallet movers, when it was better to provide MHE, and in what situations the best option was to use a working party of Marines to manually load and unload the aircraft.

Our project accomplished this by answering the following questions:

- Which sizes and types of operations would benefit from a robotic pallet mover and which would not? The entry argument to the question was to define the operationally relevant scenarios that we would investigate and model. The scenarios we initially looked at were MEU sized FARP, disaster relief, and combat resupply of EFSS 120 mm mortar rounds.
- When is it better to load or unload using a working party of available Marines? When is it better to bring in and use MHE? In the operationally relevant scenarios when a robotic pallet mover is beneficial, what are the quantified benefits in terms of time, cost, and manpower? Do these benefits justify procuring robotic pallet movers?
- What is the anticipated logistics cost and footprint over the life cycle of the system?

D. SCOPE

This project focused on determining the feasibility of the system under design and used the performance parameters and logistic requirements of the XRP to determine under what circumstances the system provided the most benefit to the users. The intent of this report is to provide an assessment of three different ways to load and unload EFSS loads from MV-22 and CH-53 aircraft with sufficient detail to allow the PdM to make a determination when to employ each of the systems considered. The report contains information supporting the recommendations.

The project modeled both the technical performance and life cycle cost. The project modeled the technical performance of loading and unloading cargo from an aircraft using the XRP and two current methods. Although an automated pallet mover may be used in conjunction with other transportation assets, the current intended use is only for the MV-22 and the CH-53, therefore the project only considered these two airlift assets.

The cost evaluation included the cost of engineering development, system procurement, disposal, consumables, transportation of the cargo-moving assets, expected maintenance and repair costs, training costs of assets, and all other operational, maintenance and logistics costs of the XRP.

Throughout the evaluation, a number of assumptions were made to refine the scope and effectively manage the limited available resources. These assumptions were:

- the pallet mover can operate successfully in any environment that is suitable for an aircraft to land
- size of operation is an MEU (12 MV-22s and 4 CH-53s in total, not all are for resupply efforts)
- the pallet mover is primarily for EFSS support, with additional capability being assessed only as time permits

The environmental assumption was based on the capabilities that Stratom proposed for the XRP in addition to the current capabilities of airlift assets. The number of aircraft available for a given resupply mission are limited by other mission priorities. The project made the assumption to limit the number of aircraft available for a resupply mission to less than that of the aviation combat element of a MEU.

E. SYSTEMS ENGINEERING PROCESS

When the evaluation began, the team considered several systems engineering models, such as the V model and Spiral development. The team ultimately selected a tailored waterfall process that incorporates significant feedback between each of the stages and incorporates a well-defined customer need. The project evaluated an existing system that was proposed to fulfill a need, and the modified waterfall allowed for focus on the process rather than realizing a product. Additionally, the feedback loops in the waterfall method worked well for modeling and simulation, as they allowed for modifications of unique parameters and reassessments of all previous stages. Bahill and Gissing (1998) described a baseline waterfall method.

The tailored systems engineering process, shown in Figure 7, began with a thorough understanding of the customer’s needs, which resulted in the definition of the parameters with which the stakeholders were concerned and resulted in a set of Stakeholder Needs (Process 0 in Figure 7). The identification of the stakeholders' needs and constraints imposed on the project lead to the definition of a problem statement. The Problem Space Exploration (Process 1) defined what the stakeholders required to meet their needs and bounded the project in terms of cost, schedule and performance.

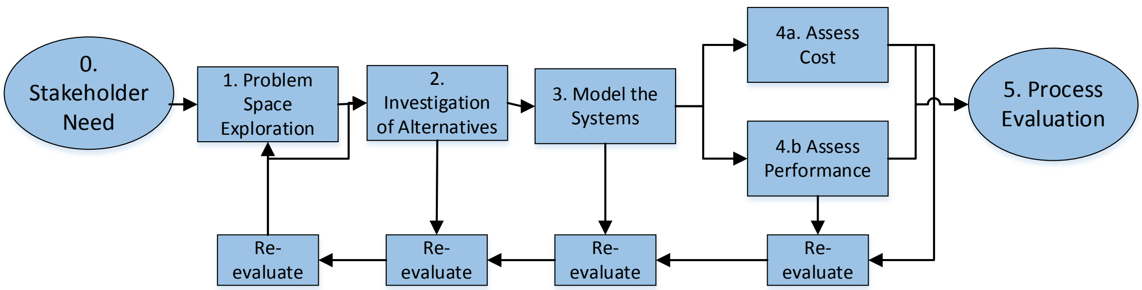

Figure 7. The Tailored Waterfall Process

The Problem Space Exploration fed the next stage of the process, Investigation of Alternatives (Process 2), by providing a trade space that served as the basis for either excluding or evaluating each of the possible alternatives. This stage produced outputs resulting in a comprehensive understanding of the known alternative methods in an attempt to meet the needs. At the completion of the Problem Space Exploration stage, we better understood the relevant performance and cost parameters that formed the baseline for developing a model of the system of each alternative.

The team performed modeling and simulation as part of the next step, Model the Systems (Process 3) for technical performance parameters using ExtendSim. We defined the performance parameters and capabilities of the XRP units through the program requirements. We completed cost models of the system using Excel. The project determined that using a model consisting of scale models, prototypes, or other physical elements was not necessary, because a computer-based simulation based on the known capabilities was sufficient for the scope of the overall evaluation.

The output of the modeling and simulation runs delivered performance data in the areas of the stakeholders' needs. The team fed outputs of both cost and performance models into the Assess Cost and Assess Performance stages (Process 4a and 4b). The team completed the assessments of Cost and Performance in parallel for each phase of the model. The parallel effort gave a complete assessment of each modeled system and identified whether a solution was technically feasible and affordable. The team analyzed these output data sets and evaluated the outputs against the stakeholders' requirements and used to determine the next iteration of the system model.

Finally, the project developed an overall Process Evaluation (Process 6) of the possible alternative solutions in the context of an operational environment, logistics footprint impact and stakeholders' needs. The evaluation provides an overall quantification of the performance, benefits and impacts of each alternative.

Following the completion of each of the technical processes, the team re-evaluated the solution path in terms of the problem statement, stakeholder needs, and alternative analysis. This re-evaluation confirmed that the problem was being approached in the correct manner.

II. PROBLEM SPACE EXPLORATION

The current EFSS has capability gaps that the XRP can possibly solve. This analysis explored the current capability gaps, verified claims of the proposed performance of the XRP, and investigated use case scenarios in order to determine the potential benefits of the XRP system.

To understand the problem in more detail, a stakeholder analysis was conducted to learn more about what the XRP must do, and to define the system requirements more clearly. Stakeholders were identified as individuals or organizations that can be impacted positively or negatively by a project. The main stakeholders for this analysis were the people that will be making programmatic decisions throughout the acquisition life cycle of the XRP and will use this analysis to make better decisions. The other stakeholders for this analysis were the people that would operate and maintain the XRP.

The derived system requirements from the stakeholder analysis were compared to the existing set of requirements provided in the RIF. The comparison revealed requirements that were good, bad or even missed. Appendix B lists recommendations for these requirements.

A. STAKEHOLDER ANALYSIS

1. Product Manager (PdM FSS, MCSC)

PdM FSS is the main stakeholder for this analysis; he is the main decision maker during the acquisition life cycle of the XRP. The PdM is in control of the budget and schedule during acquisition and initial fielding of the system. The PdM needs information to make crucial programmatic decisions before moving beyond the RIF. His top concern is to close the current capability gap and build the right solution for the EFSS units within the constraints of budget and schedule. This capstone project provides the PdM beneficial information such as: clear and correct requirements that express all stakeholders' needs, validation and verification of these requirements and a clear understanding of the XRP capabilities to move cargo to and from USMC aircraft. Also, this report provides critical information such as projected cost estimates and logistics analysis (e.g., spare parts, training, packing/handling). The PdM can use this information to make programmatic decisions beyond the RIF and have a clear understanding of the capabilities of the XRP solution.

Systems Engineering, Interoperability, Architecture, and Technology (SIAT) is the organization within MCSC that is "responsible for leading Marine Air-Ground Task Force systems engineering and integration efforts, ensuring Marine Corps systems interoperability with coalition and joint forces, and identifying and pursuing science and technology transition opportunities for Marine Corps systems" (Marine Corps Systems Command 2016, 1). Marine Corps Tactical Systems Support Activity (MCTSSA) "provides test and evaluation, engineering, and deployed technical support for USMC and joint service command, control, computer, and communications (C4) systems throughout all acquisition life cycle phases" (MCTSSA 2016, 1).

Together, MCTSSA and SIAT are responsible for formally assisting the PdM to procure the XRP if the PdM decides to move beyond the RIF. The systems engineering process that follows the Department of Defense (DOD) system acquisition framework would mainly be the responsibility of SIAT. They would support the verification and validation during the material solution analysis, technological development, engineering/ manufacturing, production/deployment and operations/support. Test and evaluation of the communications aboard the XRP would be executed by MCTSSA and would feed into SIAT's system engineering process. Together, MCTSSA and SIAT are the PdM's technical advisors. They do not want the PdM to make decisions solely from the RIF. Their top concern is to understand the technical feasibility of the XRP and ensure if the PdM does move beyond the RIF, the XRP will in fact close the capability gap.

2. Expeditionary Fire Support System Units (USMC Personnel)

The current EFSS encompasses "a Prime Mover vehicle, 120 mm towed rifle mortar weapon, a family of insensitive munitions (IM) compliant ammunition and the ammunition trailer" (General Dynamics 2016). The EFSS units will ultimately operate and maintain the XRP system. The proposed XRP could supplement or replace the current resupply methods that would increase productivity and decrease the workload associated with ammunition resupply. This capstone project is important to the EFSS units because it will explain how the XRP can possibly make an impact on the current capability. The EFSS units' top concerns are in the areas of operation, maintenance, safety, and efficiency. They want to know how the XRP would reduce their exposure on the battlefield during ammunition resupply, decrease the time it takes to unload and load from USMC aircraft, and reduce the laborious workload to unload and load. Reducing the EFSS unit's exposure on the battlefield will decrease their susceptibility to an attack or ambush by enemy forces.

Using the "significant" engineering rule of thumb, the aircrews require the XRP to reduce loading and unloading times by 10% and not exceed more than 10% of added weight to their aircraft.

3. MV-22 and CH-53 Aircrews

The MV-22 and CH-53 aircraft crews will ultimately be in charge of transporting the XRP system with the resupply to and from an austere environment. They desire a solution that will decrease loading and unloading times and still allow the cargo to be secured in the aircraft quickly and efficiently without damage or performance degradation to the aircraft. Fueling and arming of an assault support aircraft can be accomplished in about 20 to 30 minutes; fueling takes 10 to 15 minutes and arming takes the rest of the time (United States Marine Corps 2001). Aircrews and their aircraft need to be ready to go at all times. The more time it takes to load and unload an aircraft, the longer it takes to support the Marines. Every minute counts in times of war, a time reduction to load and unload an aircraft can make a significant difference to support Marines on the battlefield.

Using the significant engineering rule of thumb, the aircrews require the XRP to reduce loading and unloading times by 10% and not to exceed more than 10% of added weight to their aircraft.

4. Stratom (Automated Cargo Mover Prime Contractor)

Stratom is the developer of the XRP. While they will have no influence on the evaluation of their XRP solution, they prefer the analysis to support the procurement of the XRP by the PdM. As a business, Stratom's top concern is the success of their business through the procurement of the XRP and keeping their customers happy. Stratom wants to establish a trustworthy relationship with the PdM, USMC units and stakeholders to identify what requirements are in or out of reach due to the current limitations of technology. Stratom needs well-written, feasible, and testable requirements to develop an operationally effective and suitable system for the USMC units. By having well written requirements, Stratom can determine which requirements are feasible. Stratom wants the XRP to meet all requirements stated in the RIF, along with corrected requirements that were incorrect or missed from the original analysis. Stratom will be heavily interested in the life-cycle cost estimate, logistics analysis, and the approved acquisition objective estimate provided in this report.

5. Stakeholder Analysis Takeaways

The stakeholder analysis provided a better understanding of the system requirements and what the XRP must do. The PdM wants to close the current capability gap and build the right solution for the EFSS units. The projected cost estimates and logistics analysis from this analysis are beneficial to make crucial programmatic decisions before moving beyond the RIF. EFSS units want to understand if the XRP would reduce their exposure on the battlefield during resupply, and decrease the time it takes to load and unload from USMC aircraft. They require the XRP to be capable of carrying 10% more capacity during an operation, decrease unload and load times from CH-53 or MV-22 by 10%, and would not incur a maintenance cost of 10% more than the current resupply methods. The aircraft crews would also be interested in a 10% reduction in load and unload times. Additionally, the air crews are interested in not exceeding more than 10% of added weight to their aircraft.

Stratom wants the XRP to be successful at meeting all requirements. They want to stay in business and keep all stakeholders happy. This capstone project provides them clarification on requirements (e.g., missed, incorrect, infeasible) to continue to develop an operationally effective and suitable system for the EFSS units. They also are heavily interested in the life-cycle cost estimate and logistics analysis.

B. PEER SYSTEM INTERACTION

The XRP operates in conjunction with other systems, and it impacts and is impacted by many of them. Notable systems that both impact and are impacted by the system are: (1) the Marines of the receiving units who will receive supplies and potentially have a reduced burden of loading and unloading the supplies; (2) the aircraft and their designs will limit the XRP designs, as will maintenance concerns; (3) the supplies may have to be altered depending on the performance of the XRP. Additionally, other logistical elements, such as fuel and spare parts concerns, will both be impacted by and have an impact on the XRP system. Finally, the natural environment is a system that will affect the XRP but is not impacted by the system. Figure 8 identifies the interactions of the XRP to other system.

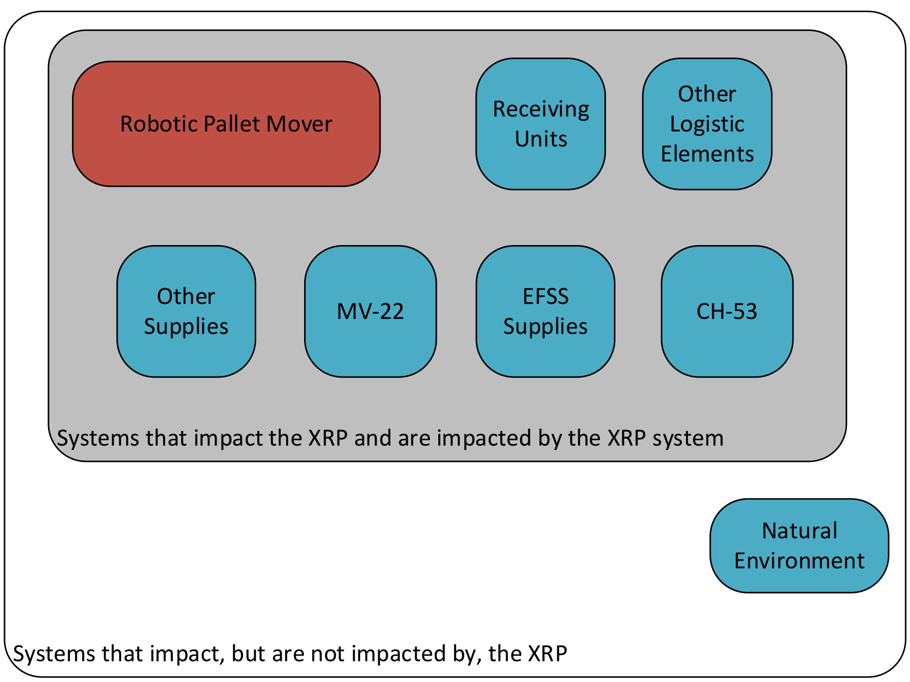

Figure 8. Context Diagram for XRP

C. TACTICS, TECHNIQUES, AND PROCEDURES

1. Tactics, Techniques, and Procedures Defined

Tactics, techniques, and procedures (TTPs) are standard operating procedures developed for accomplishing tasks by the user. The composite, non-doctrinal definition of TTP is “Tactics, Techniques, and Procedures refer to general and detailed methods for using equipment and personnel to accomplish a specific mission under a particular set of conditions” (U.S. Army Research Institute for the Behavioral and Social Sciences 2010, B-8). These TTPs assist the military in maximizing efficiency and reducing costs, while reducing operator risk and improving safety. By developing procedures that can be trained and are repeatable, operators become proficient in the tasks for which they are assigned. These procedures are captured in “living” documents which evolve and are updated as lessons are learned, both positive and negative. This section discusses the specific TTPs for how the Marine Corps EFSS currently performs resupply using the CH-53 helicopter and MV-22 tilt-rotor aircraft, as well as general TTPs for using MHE and hand loading.

2. Expeditionary Fire Support System

The EFSS is a component of field artillery, whose mission is to “destroy, neutralize, or suppress the enemy by cannon, rocket, and missile fires” (United States Marine Corps 1996, 17) and consists of “two Prime Mover vehicles, 120 mm towed rifle mortar weapon, a family of insensitive munitions compliant ammunition and the ammunition trailer” (General Dynamics Ordnance and Tactical Systems 2008, 2).

Although the XRP is capable of transporting a myriad of supplies, emphasis was placed on ammunition resupply and the PM-T and the ammunition trailer (AT) components of the EFSS. The PM-T tows the ammunition trailer, both of which were designed to meet the MV-22’s width, payload, floor-loading and tie down requirements. The ammunition trailer can carry a maximum of 30 120 mm rifled mortar rounds having a maximum vehicle weight capacity of 3500 lb. (United States Marine Corps 2013) which includes the payload.

3. Methods for Ammunition Resupply

The ammunition supply units are typically consolidated with the field units to provide the required support, of which there are three methods of ammunition resupply. The first method of ammunition resupply is the double loop method, where the ammunition is picked up from the ammunition transfer point (ATP) and taken to a flat rack transfer point where it waits for empty flat racks from the EFSS units, as seen in Figure 9. A flat rack is a component of a palletized load system, used for transporting ammunition. The empty flat rack is exchanged for one in a combat loaded configuration, at which time the EFSS unit driver returns to the EFSS unit location with a loaded flat rack, and the ammunition section chief returns to the ATP to receive more ammunition. When proper coordination has been conducted, "this is the fastest method of ammunition resupply" (United States Marine Corps 1996, 12-5).

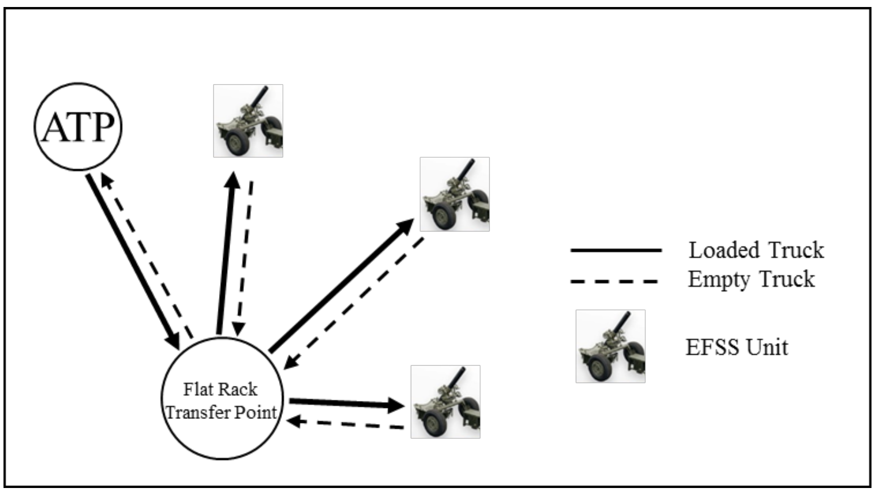

Figure 9. Double Loop Method of Resupply. Source: United States Marine Corps (1996, 12-3).

The second ammunition resupply method is the single loop, or push to EFSS unit method. Here, the ammunition is pulled from the ammunition transfer point and delivered directly to the EFSS unit position and can be seen in Figure 10. This method requires the driver to find the EFSS unit and ammunition transfer point and is affected by operating area familiarity and urgency for ammunition by the users (United States Marine Corps 1996).

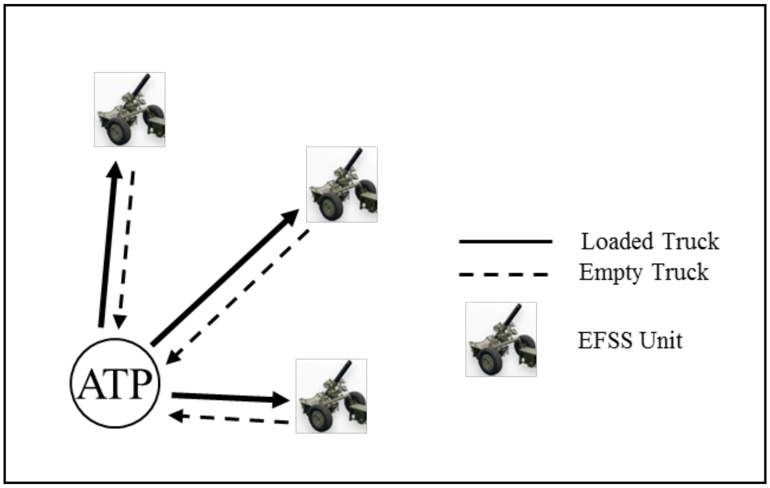

Figure 10. Single Loop Method of Resupply. Source: United States Marine Corps (1996, 12-3).

The third method of ammunition resupply uses a rearm, refuel and resupply point where ammunition is staged along the anticipated movement route as seen in Figure 11.

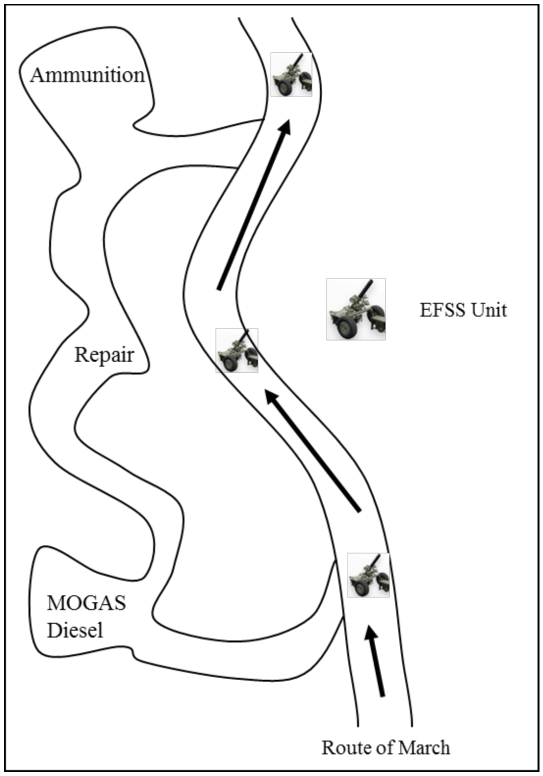

Figure 11. Rearm, Refuel and Resupply Method Source: United States Marine Corps (1996, 12-5).

The firing unit of the EFSS has the personnel and equipment capable of performing ammunition resupply, all of which are capable of being internally transportable on the CH-53 and MV-22 aircraft.

4. Aircraft Loading of the Expeditionary Fire Support System

Per the EFSS Technical Manual, Section E-10, all procedures related to the preparation and transport of the EFSS PM-T and AT are applicable to both the CH-53 and MV-22 (United States Marine Corps 2013). There are no load restrictions for the CH-53, allowing the AT to carry a full complement of 30 rounds. When transported on the MV-22, the ammunition trailer must be limited to a maximum of 24 rounds, due to floor-loading requirements (United States Marine Corps 2013). The MV-22 is the primary aircraft for transport of the EFSS, with two MV-22s being required to transport a complete EFSS. One MV-22 transports the prime mover-weapon, 120 mm mortar and two cannoneers, with the second aircraft transporting the PM-T, ammunition trailer, and three cannoneers (United States Marine Corps 2013). Cannoneers are Marines trained in the use and operation of the EFSS. There are two methods of embark and debark of the PM-T and AT onto the MV-22, with detailed step-by-step instructions given in Appendix E of the EFSS technical manual.

The PM-T and AT may be pushed-in (embark) and driven-out (debark). When pushed in, the AT is pushed by the PM-T into the cargo bay of the MV-22, disconnected from the PM-T and pushed into position by hand. The PM-T is then driven into the aircraft and reconnected to the AT. A second way to back-in the AT is to use the MV-22 winch to pull the AT into the aircraft. Once the AT is in position, the PM-T is driven into the aircraft, and both the PM-T and AT secured to the MV-22 with proper tie downs. Once the aircraft reaches its destination, both the PM-T and AT can be driven off of the aircraft.

The PM-T and AT may also be driven-in (embark) and backed-out (debark) of the MV-22. The PM-T and AT are driven straight onto the aircraft to the appropriate position and tied down. When the aircraft reaches its destination, the tie-downs are removed from the PM-T and AT and the vehicles slowly backed out of the MV-22.

5. General Aircraft Loading Procedures

When conducting general loading of aircraft, without specific procedures such as outlined for the EFSS, the “three elements of proper aircraft load planning are weight, balance, and restraint” (Naval Air Systems Command 2015, 4–1). The cargo must not exceed the carrying capacity of the aircraft, be loaded so as not to shift the center of gravity of the aircraft outside of acceptable limits for safe flight and must be restrained to prevent shifting during flight.

When loading cargo using MHE, such as fork lifts, care must be taken to ensure proper clearances between the MHE and aircraft. Considerations for overall weight, concentrated floor loads, cargo roller rail strength and center of gravity must be determined as the aircraft is loaded.

When loading or unloading using only a working party, numerous restrictions apply in order to protect the health of those involved. Table 1 identifies the maximum one-time manual lift for a single person of an object with uniform weight distribution and a maximum size of 18 inches x 18 inches x 12 inches (Department of Defense 2012). Due to the nature of loading and unloading of cargo, a one-time lift is unlikely and impacts the maximum allowable weight of the object being carried. If a load is lifted more than one time in five minutes or 20 times in eight hours the allowable weight is reduced to account for the frequency of the lift (Department of Defense 2012). If the depth of the load exceeds 12, 36, or 48 inches, the allowable weight is reduced by 33, 50, or 66 percent respectively (Department of Defense 2012). For a two-person lift, the maximum allowable weight is doubled. Any lifts greater than a two-person lift increases the maximum allowable load by 75 percent of the individual load per person (Department of Defense 2012). Table 1 summarizes the maximum allowable lifting weight limits for a single person lift.

Table 1. Maximum Weight Limits. Source: Department of Defense (2012).

Handling Function	Population	
	Male and Female	Male Only
Lift an object from the floor and place it on a surface equal to or greater than 152 cm (5.0 ft) above the floor.	14 kg (31 lb)	21.9 kg (48 lb)
Lift an object from the floor and place it on a surface not greater than 152 cm (5.0 ft) above the floor.	16.8 kg (37 lb)	25.4 kg (56 lb)
Lift an object from the floor and place it on a surface not greater than 91 cm (3.0 ft) above the floor.	20 kg (44 lb)	39.5 kg (87 lb)
Carry an object 10 m (33 ft) or less.	19 kg (42 lb)	37.s kg (82 lb)

Independent of the method used, three elements are involved in the loading and unloading of cargo and therefore require detailed information on the cargo prior to transport. The first of the three elements is the supporting unit which requests the mission and has the primary responsibility of ensuring the cargo is loaded properly onto the aircraft with the necessary tie-downs and that it does not violate any of the space or weight limits of the aircraft (Headquarters, Department of the Army 1997). The second element is the aviation unit which coordinates between the other two elements and is required to be knowledgeable on both the limitations of the aircraft and the security, safety, and technical details of the cargo being transported (Headquarters, Department of the Army 1997). The third element is the receiving unit that is taking control of the cargo upon unloading and is responsible for the landing zone, as well as preparing any cargo that will be loaded back onto the aircraft (Headquarters, Department of the Army 1997). The purpose of the first two units, during a resupply scenario is to ensure the third unit receives the items it requires to perform its mission.

6. Aircraft Landing Zones

The potential landing zones for cargo loading and unloading are highly variable. They range from the most controlled cases where established bases have designed permanent landing zones to natural terrain where logistical and tactical considerations need to be factored into the mission scenario. Where a landing zone is not permanently established, site selection and sizing depends on many factors, including aircraft type, unit proficiency, nature of the load, climatic conditions, terrain conditions, aircraft approach, and time of day (Headquarters, Department of the Army 1997). The landing zone will also dictate the method for offloading cargo based on the material handling equipment that is available to load and unload cargo.

7. Anticipated TTP Updates

The goal of the XRP is to adapt the current TTPs to be as autonomous as possible. The XRP is intended to achieve this goal by removing the majority of manpower required to support the loading and unloading of cargo, as well as the transportation of resupply items from the aircraft to the EFSS unit. The overarching tasks remain very similar, starting with the need to secure, and therefore unsecure, the cargo and XRP to the aircraft. The XRP cannot perform this task autonomously and requires minimal updates to the TTPs. Figure 12 displays the XRP in the load and unload configuration. The XRP's winch can pull loaded pallets up the ramps or slowly lower loaded pallets to the ground. Once the pallet is on the top surface, the XRP returns to the standard configuration and the pallet and cargo is secured to the XRP using the tie downs.

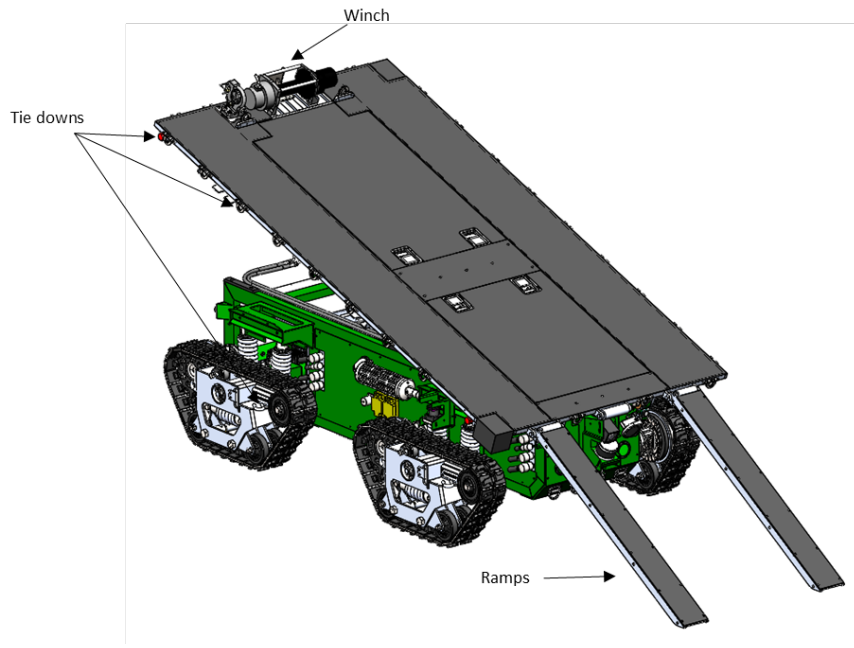

Figure 12. Load and Unload Configuration. Source: Stratom (2016).

The load and unload of the cargo onto the aircraft will be performed by the XRP under the direct control of a remote operator, who may also control movement to and from the EFSS unit. Figure 13 shows how the XRP can also move between predetermined waypoints set by the operator, becoming fully autonomous. The use of remote control or waypoints eliminates the need to transfer the cargo to a flat rack for transport.

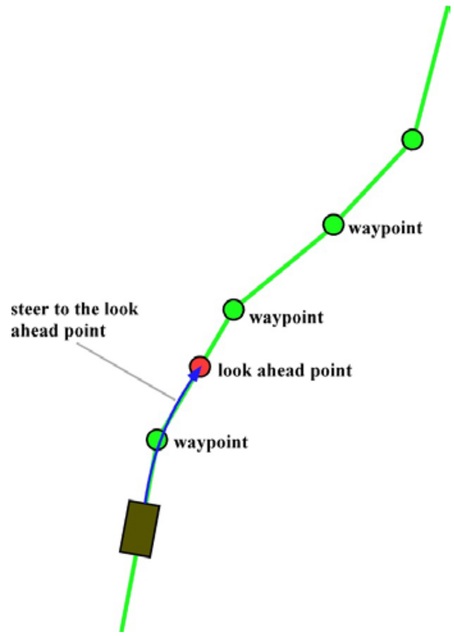

Figure 13. Waypoint Steering. Source: Stratom (2016).

8. Key TTP Requirement Takeaways

Investigation of how the currently fielded system is operated and supported allowed for some key requirements to be documented for application during the modeling efforts. The Requirements Analysis section details the specific requirements. The most important requirements dealt with how the XRP interfaces with other fielded systems due to the need to operate as a system of systems, specifically those dealing with dimensions and weight where a noncompliance would result in not obtaining approval for transport on the MV-22 or CH-53. The requirement for safe transportation of cargo on aircraft does not change when fielding an autonomous system. The key requirements that drive safe transportation, without requiring a change to the aircraft, force the method of securing the XRP to be similar to current cargo loads. When transported on aircraft, the XRP must not violate fuel, battery, weight and space constraints nor cause electrical interference with the aircraft. This requirement has a significant impact on the carrying limits of the XRP due to its inherent weight that must be accounted for in place of cargo. The team used this information to help define scenarios, mission profiles and support assumptions. The models of ammunition resupply directly supported the discrete event models of operationally relevant scenarios in order to quantify the potential benefits and impacts to the Marine Corps, and specifically the EFSS program office.

THIS PAGE INTENTIONALLY LEFT BLANK

III. REQUIREMENTS ANALYSIS

Requirements are crucial and must be understood by all stakeholders. They must be correct, feasible, unambiguous, and verifiable. A requirements analysis was conducted to ensure requirements were clear and complete. "Requirements analysis, also called requirements engineering, is the process of determining user expectations for a new or modified product. These features, called requirements, must be quantifiable, relevant and detailed" (Rouse 2007). The requirements of the XRP were derived from the RIF critical design review (CDR) XRP presentation provided by the prime contractor, Stratom Inc. The RIF provided a good start to the requirements but since the XRP is in early development, it is expected that requirements have been overlooked or even missed. The requirements analysis provides a more in-depth review to ensure quality requirements and add or remove requirements that may have been overlooked or missed.

A. PROGRAM REQUIREMENTS

"The Rapid Innovation Fund provides a collaborative vehicle for small businesses to provide the department with innovative technologies that can be rapidly inserted into acquisition programs that meet specific defense needs" (Defense Innovation Market Place 2016). One of the main purposes of the RIF was to identify requirements for the development of a resupply system solution. Since the XRP is in its infancy of development, there has been no formalized requirement documentation.

The CDR grouped requirements in the following areas: Mission, Environmental, Safety, MV-22 Load/Unload, CH-53 Load/Unload, Guidance Navigation and Control, Human Interface, Electrical, Power, Communication, Propulsion, Winch/Cargo, Lift and Sensors (Stratom 2016). Within these areas, 85 requirements were extracted and examined. These requirements are listed in Appendix A. Highlighted mission level requirements for the XRP were extracted from the CDR and are listed below:

> The XRP SHALL be capable of self-propelled loading/unloading into an MV-22 aircraft without Material Handling Equipment (MHE).

> The XRP SHALL be capable of transporting cargo at least 800 [m] for un-palletization of the cargo.
>
> The XRP SHALL be capable of transporting operational cargo over terrain with a Terrain Complexity Categories for Ground Robotics greater than or equal to 3.[1]
>
> The XRP SHALL provide features for the safe operation of the system around personnel and aircraft.
>
> The XRP SHALL NOT contain any components/problems/issues that cause the vehicle to become incapable of attaining flight certification for the MV-22.
>
> The XRP SHALL have a total operational weight of less than or equal to 4907 lbs. (Stratom 2016, 22)

B. REVIEW OF REQUIREMENTS

Figure 14 illustrates the requirement analysis process. It lays out the necessary steps from the input and the controls to the outputs. The Basic Review was a simple method to verify if each of the requirements in Appendix A contained any word of obligation (e.g., shall, will, must) or minimum and maximum values. The input to the Basic Review block consisted of all the requirements in Appendix A and the output was a subset of fifteen requirements. There was one input and two controls for the detailed requirement assessment block: the TTP, Stakeholder analyses were the controls and the Basic Review output was the sole input. The outputs were two lists, one of which was the conflicts between requirements and stakeholder needs and the other, a list of impacted TTPs. SMARTT is an acronym that stands for Specific, Measurable, Attainable, Realistic, Time-bound and Traceable. One can assess a system's requirements based on adherence to each of these attributes. The output of the Basic Review block was the only input for the SMARTT review and after its application, the results were a list of well-written requirements.

[1] Terrain complexity is a value assigned to the roughness of land. Stratom has a proprietary formula to calculate terrain roughness through the tilt/track data. A value of 1 to 5 will be given, 5 being extremely rough land.

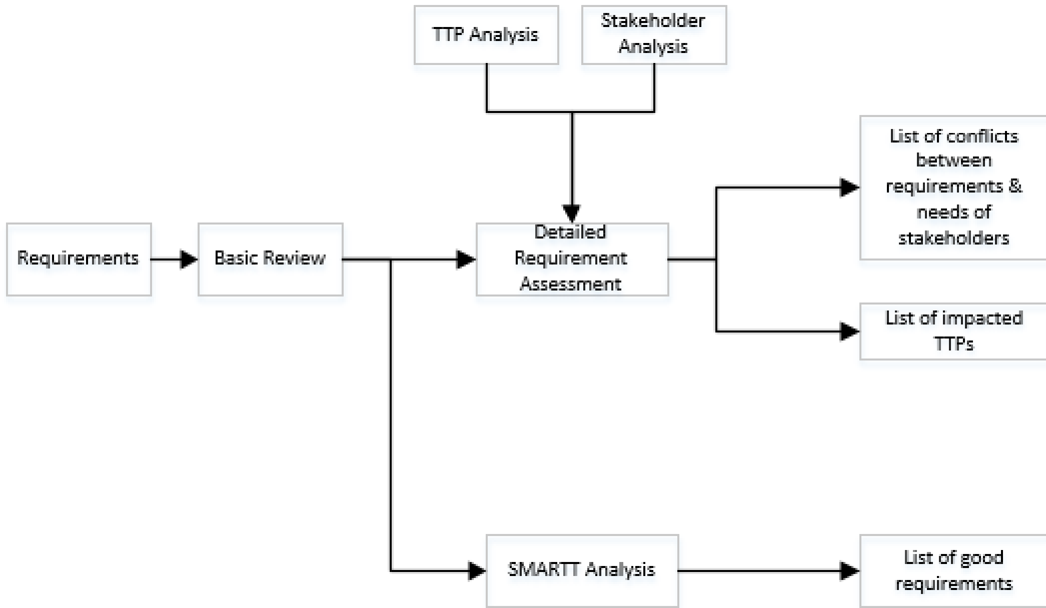

Figure 14. Requirement Analysis Process

1. TTP Review and Stakeholder Review

The TTPs were reviewed against the requirements from the Basic Review and as a result it was determined that the requirements in Table 2 will cause changes in some of the TTPs that are associated with resupply missions. The requirements for the XRP, which can be considered design requirements, will have no effect on the TTPs. These requirements are associated with the XRP empty weight, frame size, longitudinal grade capabilities, and top plate angle and failure modes.

Table 2. TTP and Stakeholder Review

Highlighted Mission and Derived Requirements	**Will this requirement cause a change in current TTPs?**	**Is this in line with what is known about the stakeholders?**
The XRP SHALL be capable of self-propelled loading into an MV-22 aircraft without Material Handling Equipment (MHE).	Yes	Yes
The XRP SHALL be capable of self-propelled unloading from an MV-22 aircraft without Material Handling Equipment (MHE).	Yes	Yes
The XRP SHALL have a total operational weight of less than 4907 [pounds].	Yes	Yes
The XRP will have a total loaded weight under 4907 pounds. The vehicle will weigh less than 2150 pounds and be able to carry 2756 pounds.	Yes	No
XRP has a Threshold of 1.25 m/s and Objective of 4.47 m/s	Yes	Yes
XRP must be able to carry 2756 pounds	Yes	Yes

The loading and unloading of aircraft using autonomous capability, the loaded weight, center of gravity and tie down provisions will all cause adjustments in the current TTPs associated with using aircraft for resupply missions. The TTPs will be altered by the carrying capacity and speed at which the XRP can load and unload aircraft when some of the concept of operations (CONOPS) are substituted for hand loading and the use of MHE. An analysis of the intended CONOPS and TTPs for employment of the XRP was conducted in order to fully develop the requirements. The XRP's top level function of "Transport Supplies" was decomposed per the intended CONOPS and TTPs to further refine the requirements. A typical mission profile for the loading and transport of supplies by the XRP follows:

- Prepare the cargo for loading onto the aircraft.
- Load cargo onto the aircraft.

- Secure cargo onto the aircraft.
- Aircraft arrives at the fire base.
- Cargo is unsecured from the aircraft.
- Cargo is removed from the aircraft and staged to be stored.
- Prepare the cargo for loading onto the aircraft.
- Load cargo onto the aircraft.
- Secure cargo onto the aircraft.
- Cargo is unsecured from the aircraft.
- Cargo is removed from the aircraft and staged to be stored.

By conducting an analysis of the CONOPS and TTPs for each of the intended mission profiles of the XRP, requirements were developed for integration of the cargo with the XRP, integration of the XRP with the specific aircraft, capability limitations of the aircraft, and storage requirements. The CONOPS and TTPs also helped to determine the performance requirements of the XRP for terrain capabilities, speed and range. An analysis of the CONOPS and TTPs was necessary to determine the physical, functional and operational requirements for the XRP.

Most of Stratom's requirements for the XRP are in line with the viewpoint of the stakeholders with only one exception, the combined weight of the XRP and its load. This requirement is well below the maximum loading capacity for an MV-22 ramp during ground operations. The reasoning for selecting 4,907 pounds as the weight requirement of the XRP and its load is not known. This particular requirement will be discussed further in Section 4.

2. Added Requirements

From the stakeholder analysis, the following requirements were added to demonstrate greater efficiency of the XRP solution, to the current EFSS resupply methods. The assigned values are estimates that would display better efficiency; since there is no standard value for "efficiency," values may change. The following percentages come from the engineering rule of thumb, where “significant” means ≥ 10% change.

- The XRP shall decrease time to unload CH-53 or MV-22 by 10%.
- The XRP shall decrease time to load CH-53 or MV-22 by 10%.
- The XRP shall decrease time to deliver cargo from aircraft to operational area by 10%.
- The XRP shall decrease time to return from operational delivery back to aircraft by 10%.

3. SMARTT Review

The initial SMARTT review was an analysis of the XRP requirements against the SMARTT objectives. For each of the fifteen remaining requirements in Table 3, the first objective, Specific, was applied to discover the number of requirements per statement and if that statement was clear and unambiguous (without any subjective terms). The second objective, Measurable, was applied to identify a unit of measurement and whether that objective could be quantified. The third objective, Attainable, was considered to determine whether a theoretical solution existed and whether that requirement could be realized when other factors and constraints were considered. The fourth objective, Realistic, was applied for the adequacy of allocated resources to include human capital, time and funding. The fifth objective, Time-bound, was applied to identify the inclusion of any completion date or timeline. The final objective, Traceable, was applied to reveal any other artifact that may have been used to verify or fulfill that requirement.

The results of the initial SMARTT review are shown in a matrix format in Table 3. The SMARTT objectives are listed across the top of the matrix, with the requirements shown on the left. The green check mark identifies that the requirement met that particular objective. The blue question mark indicates that a determination could not be made based on the information at hand. The red X identifies that the requirement did not meet that particular objective. It is important to reiterate that some of the requirements may seem at first to adhere to some of the attributes. However, if a requirement is not specific, it will not meet the criteria of the other attributes. As was the case for TTP and Stakeholder reviews, fifteen requirements were further challenged through the SMARTT review.

Table 3. SMARTT Review of XRP

Legend: ✓=Met; ✗ = Not Met ?=TBD	**S**pecific		**M**easurable		**A**ttainable		**R**ealistic	**T**ime-bound		**T**raceable	
Highlighted Mission Requirements	Clear/No ambiguity	Avoid double requirements	Is it quantitative?	Specific but no benchmark	Is there a theroretical Solution?	Is the goal realistic based on other constraints?	Are the allocated time, personnel, & budget adequate to achieve this requirement?	Date of completion?	How fast should this requirement be completed?	How is this requirement met by other artifacts?	How is this requirement verified by test artifact?
The XR-P SHALL be capable of self-propelled loading into an MV-22 aircraft without Material Handling Equipment (MHE).	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗
The XR-P SHALL be capable of self-propelled unloading from an MV-22 aircraft without Material Handling Equipment (MHE).	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗
The XR-P SHALL be capable of transporting operational cargo over terrain with a Terrain Complexity Categories for Ground Robotics greater than or equal to 3 [category].	✓	✓	✓	✓	?	?	?	?	?	?	?
The XR-P SHALL have a total operational weight of less than 4907 [lbs.].	✓	✓	✓	✓	?	?	?	?	?	?	?
Derived Requirements											
Frame size is designed for MV-22 and CH-53 aircrafts. 60 inch max width. 60 inch max height.	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗
Frame size is designed to hold: Standard metal & wooden pallets.	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
The XR-P will have a total loaded weight under 4907 lbs. The vehicle will weigh less than 2150 lbs and be able to carry 2756 lbs.	✓	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗
XRP has a Threhold of 1.25 m/s and Objective of 4.47 m/s (carrying 2700)	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
XRP must be able to carry 2756lbs	✓	✓	✓	✓	?	?	?	?	?	?	?
XRP shall meet 1610(m) Mission distance	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗
XRP shall meet longitudinal grade of 60%	✓	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗
XRP shall not weigh more that 2150 (lbs)	✓	✓	✓	✓	?	?	?	?	?	?	?
XRP shall meet Top plate Angle of 4 Threshold	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗
The XR-P SHALL automatically stop in the event of a critical system failure. Note: Critical system failure has not been defined. But will be listed in Test Case/Procedure Document TP-TBD-TBD.	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗
The XR-P remote electronic stop device SHALL support operation up to 300 [m] Line of Sight.	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗

4. Detailed Review

After the SMARTT review was applied to all requirements from the Basic Review, two highlighted mission requirements and two derived requirements remained for a detailed review. Table 4 shows the category of each of the requirements for the detailed review. One of the mission requirements was that “the XRP shall have a total operational weight of less than 4907 [lbs.]” (Stratom 2016, 22). The load capacity of an MV-22 ramp for ground operations is 5,000 pounds, indicating that the 4907-pound operational weight was selected to include a 93-pound margin. The reasoning behind selecting exactly 93 pounds as the margin instead of 50 or 100 pounds is not known, but accounting for the additional weight of protective packing material made sense.

Table 4. Category of Requirements

Category	Requirements
Highlighted Mission	The XRP shall have a total operational weight of less than 4907 pounds
Highlighted Mission	The XRP shall be capable of transporting operational cargo over terrain with a Terrain Complexity Categories for Ground Robotics greater than or equal to 3 [Category]
Derived	XRP must be able to carry 2,756 pounds
Derived	XRP shall not weigh more than 2,150 pounds

Another mission requirement was that “the XRP shall be capable of transporting operational cargo over terrain with a Terrain Complexity Categories for Ground Robotics greater than or equal to 3” (Stratom 2016, 22). The terrain complexity category 3 was defined as vegetation-covered terrain and small puddles. Although this requirement may not seem to be well defined at first, one has to remember that the RIF is intended to mature this potential solution and therefore a fully-defined operational terrain may not be achievable at this point. Therefore, this requirement was found to be good thus far.

One of the remaining derived requirements was that “the XRP must be able to carry 2,756 lbs.” (Stratom 2016, 22). The XRP must be able to carry two pallets and each pallet weighed 1,369 pounds. Therefore, the total weight should be 2,738 pounds or 18 pounds less than stated in the requirement. Including padding in case there were to be a weight adjustment made sense, but the reasoning behind selecting precisely 18 pounds as the margin instead of 15 or 20 pounds is not known.

The second derived requirement was that “the XRP shall not weigh more than 2,150 lbs.” (Stratom 2016, 22). The logic behind this exact number was found by subtracting the weight requirement of the load of the XRP (2,756 pounds) from the requirement of the overall weight requirement of the XRP (4907 pounds) and its load which equaled to 2,151 pounds. Again, this one-pound margin of variation was to provide some tolerance during weighing.

IV. MODELING AND SIMULATION

The project developed a computational model for loading and unloading EFSS cargo from the two aircraft in order to evaluate the costs and potential benefits to each of the stakeholders for the XRP previously identified through the SE process. This chapter presents the methodology used to develop the performance model. This model evaluated the effectiveness of the XRP using models of a working party and MHE as a baseline for comparison. The model was developed and run in ExtendSim. The project used ExtendSim due to its ability to "Predict the effects of changes on existing systems" and "predict the behavior or performance of potential new systems" (ExtendSim 2016). The model determined the performance of parameters of interest to the stakeholders for each of the three methods investigated, as well as provide inputs for a separate cost model. The development of the model followed the path of the EFSS cargo as it transitions from a forward supply point to the specific final location, such as a gun position.

A. MODELING AND SIMULATION INTRODUCTION

The project modeled loading and unloading a Marine Corps tactical lift aircraft with an EFSS resupply load. The process began with loading an aircraft at a supply point. Next, manpower resources secure the cargo in the aircraft for a flight. The process continues with the aircraft flying to an objective location such as a firebase. At this point the aircraft lands, the appropriate cargo is unloaded since an aircraft may carry cargo to multiple locations in one sortie. The cargo delivery process results in the cargo arriving at its desired final location. Once the cargo is unloaded, an additional process can reload the aircraft with any returning cargo. The aircraft is now able to begin the return flight to the supply point. Figure 15 describes this process, where each block represents a distinct action in the process. The modeling intent was to discover the differences between each of the three methods of cargo handling: MHE, working parties and utilizing an XRP. Therefore, we did not consider activities where the values for each method will be identical, as they will not differentiate between the methods. Figure 15 highlights these activities in blue.

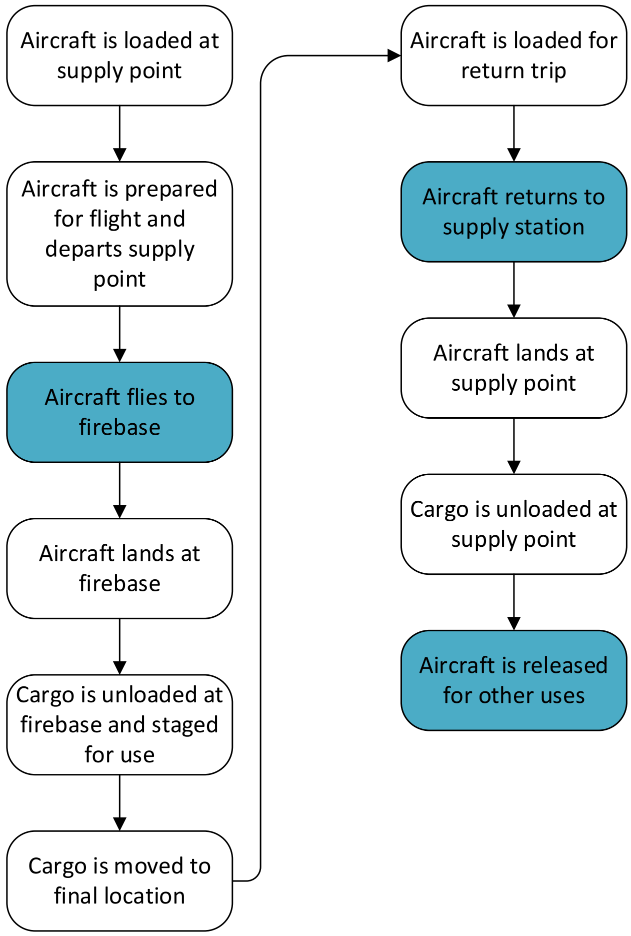

Figure 15. The Cargo Moving Process

B. SIMULATION SCOPE AND ASSUMPTIONS

Modeling and simulation of the three cargo handling methods ultimately seeks to answer the question, are XRPs beneficial to the stakeholders in their performance of moving cargo when considering the Life-cycle costs and additional logistical burden? To focus the results of the modeling and simulation effort, a number of assumptions were made.

Rotary wing and tilt rotor aircraft transfer cargo loads from a forward supply point to an operating location. The aircraft returns cargo such as unused equipment and trash in the same manner.

Similarly, the reverse of this modeling and simulation process evaluated the unloading of the aircraft. In this case, the EFSS cargo begins on an aircraft, the aircraft lands and manpower resources unsecure the cargo. Manpower resources then offload the cargo and move it to a staging point where it is transferred to an intermediate transportation asset, such as an ammunition trailer. This step is not necessary for the XRP as it has the range and movement capabilities to transfer cargo directly from the aircraft to the desired location.

We developed a number of model parameters to evaluate the performance of all considered methods of cargo handling. Table 5 identifies the parameters used to develop both the load and unload models. Table 6 presents the input parameters used unique to the load scenarios. Similarly, Table 7 presents the input parameters for the unload scenarios. The project chose source data from operationally relevant documents. Lognormal distributions accounted for human variability in the model.

Table 5. Values Used in Developing the ExtendSim Models

Input	Value	Units
XRP and Pallets per aircraft (V-22)	2	pallets/aircraft
XRP and Pallets per aircraft (CH-53)	2	pallets/aircraft
Weight per XRP	2756.0	lbs.
Weight per pallet (V-22)	4000.0	lbs.
Weight per pallet (CH-53)	10000.0	lbs.
Single person lift	56.0	lbs.

Table 6. Values Used for Developing the Loading ExtendSim Models

Input	Mean	Standard Deviation	Units
Number of prep resources	4	n/a	manpower
Time to prep per pallet load (MHE) - V-22	5.9	0.9	mins
Time to prep per pallet load (MHE) - CH-53	14.8	2.2	mins
Time to prep per pallet load (XRP)	4.1	0.6	mins
Number of load resources (WP)	4	n/a	manpower
Number of load resources (MHE)	1	n/a	manpower
Number of load resources (XRP)	1.0	n/a	manpower
Time to load per pallet load (WP) - V-22	58.2	8.7	mins
Time to load per pallet load (WP) - CH-53	146.0	21.9	mins
- Walking speed carry 50 lb	2.5	n/a	ft/s
- Distance to walk load	164.0	n/a	ft
Time to load per pallet load (MHE)	1.2	0.2	mins
- MHE speed	11.7	n/a	ft/s
- Distance to move load (MHE)	164.0	n/a	ft
Time to load per pallet load (XRP)	0.6	0.1	mins
- XRP speed	7.2	n/a	ft/s
- Distance to move load (XRP)	164.0	n/a	ft
Number of secure resources	2	n/a	manpower
Time to secure per pallet load (V-22)	4.0	0.6	mins
Time to secure per pallet load (CH-53)	10.0	1.5	mins
Time to secure per pallet load (XRP)	5.0	0.8	mins

Table 7. Values Used for Developing the Unloading ExtendSim Models

Input	Mean	Standard Deviation	Units
Number of unsecure resources	2	n/a	manpower
Time to unsecure per pallet load (V-22)	2.0	0.3	mins
Time to unsecure per pallet load (CH-53)	5.0	0.8	mins
Time to unsecure per pallet load (XRP)	2.5	0.4	mins
Number of unload resources (WP)	4	n/a	manpower
Number of unload resources (MHE)	1	n/a	manpower
Number of unload resources (XRP)	1	n/a	manpower
Time to unload per pallet load (WP) - V-22	58.2	8.7	mins
Time to unload per pallet load (WP) - CH-53	146.0	21.9	mins
- Walking speed carry 50 lb	2.5	n/a	ft/s
- Distance to walk load	164.0	n/a	ft
Time to unload per pallet load (MHE)	1.2	0.2	mins
- MHE speed	11.7	n/a	ft/s
- Distance to move load (MHE)	164.0	n/a	ft
Time to unload per pallet load (XRP)	0.6	0.1	mins
- XRP speed	7.2	n/a	ft/s
- Distance to move load (XRP)	164.0	n/a	ft
Number of transfer resources (WP)	4	n/a	manpower
Number of transfer resources (MHE)	4	n/a	manpower
Time to transfer per pallet load (MHE) - V-22	5.9	0.9	mins
Time to transfer per pallet load (MHE) - CH-53	14.8	2.2	mins
Time to move	1.9	0.3	mins
- Distance to final destination	3281.0	n/a	ft
- Ammo trailer speed	29.3	n/a	ft/s
Time to move (XRP)	7.6	1.1	mins
- Distance to final destination	3281.0	n/a	ft
- XRP speed	7.2	n/a	ft/s

The model used these parameters to predict transit time for the cargo while the aircraft is neither flying, in the process of taxing on a ramp, nor awaiting clearance to takeoff, land or move to an unloading location. In situations where the team was unable to obtain verified sources, estimated parameters were presented to the stakeholders for their acceptance.

C. OPERATIONAL-BASED SCENARIOS

Operationally-based scenarios were developed to demonstrate how cargo will be loaded and unloaded in the discrete event models.

1. Scenario 1: Unloading of Cargo from an Aircraft

The arrival of an aircraft containing cargo that needs to be offloaded and transported to a final destination triggers the start of the unload scenario. The aircraft enters a holding pattern until a landing zone is assigned. This could be an established landing pad or unprepared terrain that ground forces deem safe to land. Once the aircraft has landed, the aircraft crew begins to unsecure the onboard cargo from the aircraft tie downs. As each individual pallet of cargo is unsecured from the aircraft, an unload resource is assigned to remove the cargo from the aircraft to a location outside of the landing zone. Once all cargo has been successfully unloaded, the aircraft leaves the landing zone. Available resources transfer the cargo to a heavy lift resource for transport to its final destination, the EFSS unit. The three variants below further refine this baseline, Scenario 1:

Variant 1a: Unloading of cargo from an aircraft using a working party

The use of a working party refines Scenario 1 by designating a number of Marines as the resource that unloads the cargo directly onto the EFSS ammunition trailer for transport to the EFSS unit. Due to the weight of the cargo, each pallet load is broken down into man transportable items (or items a single person can transport). The use of a working party is the most likely variant in forward deployed locations due to the lack of material handling equipment.

Variant 1b: Unloading of cargo from an aircraft using MHE

The use of MHE refines Scenario 1 by assigning a forklift to unload the cargo from the aircraft and moving it to an area outside of the landing zone. Once the cargo has been unloaded, the forklift is free to perform another task. The crew of the EFSS ammunition trailer is then required to unpack the pallet to man transportable size for placement on the EFSS ammunition trailer. This variant of Scenario 1 is less likely to occur when compared to Variant 1a due to the lack of availability of MHE at forward operating bases and FARP sites. MHE is more likely to be available at larger airfields and aboard ship (i.e., where the cargo is coming from, not the delivery location.

Variant 1c: Unloading of cargo from an aircraft using the XRP

The use of the XRP refines Scenario 1 by removing the need for a separate unload, transport, and move resource. The unload resource is removed since the XRP is free to drive off the aircraft under the remote control of an operator once it is unsecured. The transport and move resources are not required since the XRP can travel by waypoints out of the landing zone and to the final destination.

2. Scenario 2: Loading of Cargo onto an Aircraft

The arrival of cargo that needs to be loaded onto an aircraft triggers the start of the load scenario. The cargo arrives at the necessary area to be prepared by the preparation resource for loading onto the aircraft. Once the aircraft is available, the load resources move the cargo onto the aircraft. The aircraft crew then secures the cargo to the aircraft for safe transport. The crew secures the cargo, freeing the aircraft for takeoff. The three variants below further refine this baseline, Scenario 2:

Variant 2a: Loading of cargo using a working party

The use of a working party refines Scenario 2 by designating a number of Marines as the resources that load the cargo directly onto the aircraft in man transportable items. Due to the weight of the cargo, securing it to the pallet prior to loading onto the aircraft is not possible, so this step takes place after each pallet has been fully loaded onto the aircraft. The crew secures the cargo to the pallet and then secures the pallet to the aircraft.

Variant 2b: Loading of cargo using MHE

The use of material handling equipment refines Scenario 2 by assigning a forklift to load the cargo, in palletized form, onto the aircraft. The forklift is available for another assignment once the cargo is loaded onto the aircraft.

Variant 2c: Loading of cargo using the XRP

The use of the XRP refines Scenario 2 by removing the need for a separate load resource. Manpower secures the cargo to the pallets, which are then secured to the XRP prior to arrival of the aircraft. The aircraft crew remotely operates the XRP onto the aircraft and secures the payload for flight.

D. SIMULATION DESIGN

Figure 16 shows the path the cargo takes during a typical loading operation, regardless of location, aircraft type or method used to load it. White blocks represent unique tasks modeled in the load cargo process. The model for each method followed this path. Loading cargo will follow a similar path whether it is at a supply point or at a firebase.

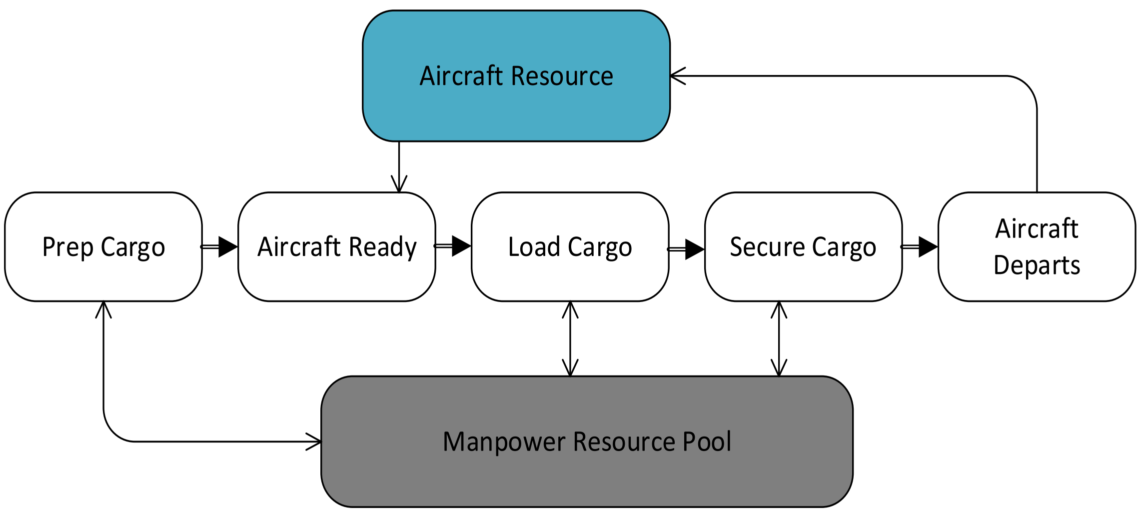

Figure 16. A Schematic of Tasks Required to Load an Aircraft Using a Working Party

In this model, the white blocks are actions that are necessary to the transportation of cargo and the grey and blue boxes are resource pools where manpower or aircraft, respectively, can be drawn from and then released when the task is completed. Cargo will begin at the prep cargo block and then follow through each of the white blocks sequentially following the double arrows. Manpower resources are utilized from respective resource pools by the process and subsequently released back to the resource pool when the operation has completed using them; the utilization and release are represented by the single arrows.

The first step, Prep Cargo, is the action of palletizing cargo whether in the standard size pallets or the ones for the XRP. Requirements to begin this step are that a cargo load must be present and all resource pools are full. For the model, cargo is assumed to be present, and the resource pool is assumed to be full to a level designated for each run of the model. Manpower from the resource pool unloads cargo. Once the cargo is prepared, the manpower resource is released. For this action, manpower utilization time increases. The output of this step is that cargo is ready to be loaded onto an aircraft.

The Aircraft Ready action is when an aircraft is in position and able to receive cargo. This block requires the inputs of cargo and an aircraft being ready. The Aircraft Ready action utilizes the aircraft resource and the aircraft. Utilization of the aircraft continues after this block is complete, therefore, the model does not release the aircraft. When the aircraft is present at the loading point, the Aircraft Ready action is complete. No time values are increasing during this step, as it is an instantaneous action. The output of this step is the aircraft is able to receive a cargo load.

The Load Cargo block is the action of physically moving of cargo onto the aircraft. To begin this block, the previous blocks of Prep Cargo and Aircraft Ready must have been completed. This block utilizes the aircraft and manpower resources, physically handling cargo, operating MHE or controlling the XRP. Separate resource pools account for these resources in each of the respective models. After the cargo is loaded, the manpower resource is released. While in this block, the aircraft usage, manpower usage, and cargo times all increase. The output of this step is that cargo is on the aircraft.

The Secure Cargo block is properly securing the cargo after it is loaded in the aircraft. To begin this block, the previous block of Load Cargo must be complete. This block utilizes resources of the aircraft and a manpower resource to secure the cargo; once the cargo is secured, the manpower resource is released. During this block, the values of cargo time, aircraft utilization, and manpower utilization increase. The output of this step is that manpower resources have secured the cargo on the aircraft.

The Aircraft Departs action represents the aircraft leaving the ramp area and beginning its mission. To begin this block, the Secure Cargo block must be complete. This block ends the utilization of the aircraft resource and does not require a manpower resource. Once the cargo reaches this block, the aircraft utilization and total cargo times stop. The output of this step is that the aircraft is able to begin other preflight activities and depart on its mission; these activities are not included as part of this model as they will be the same for all three methods being investigated.

Figure 17 shows the path the cargo takes while it is unloaded. In a similar manner to the loading operation, unloading cargo was broken down into unique tasks represented as white blocks in the model. Manpower Resource Pool is shown as a gray block, the Landing Zone Resource is a green block, and the Intermediate Movement Resource is a red block. Unloading cargo will follow a similar path whether it is at a supply point or at a firebase.

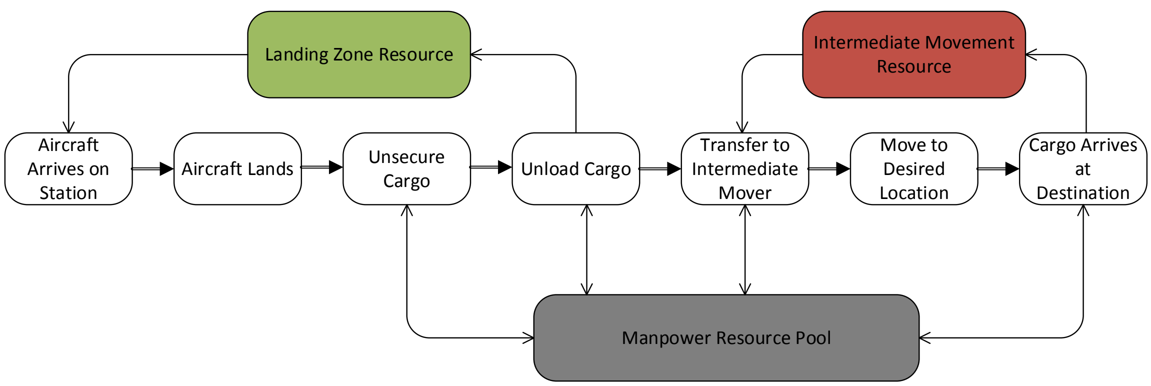

Figure 17. A Schematic of Tasks Required to Unload an Aircraft Using a Working Party

The model begins by tracking the aircraft until the aircraft have landed after which it switches to tracking individual cargo items. In the case of an EFSS resupply load, this would be a pallet of 120 mm mortar rounds. However, the model is insensitive to the type of cargo delivered. During the time that the model is tracking aircraft, the cargo times increase, as they are loaded on the aircraft.

The first action block of unloading cargo is the Aircraft Arrives on Station, either at the supply station following receiving cargo to be returned from a firebase, or while delivering cargo to a firebase. To begin this block, an aircraft loaded with cargo must be present. During this block, the aircraft resource begins utilization. Aircraft utilization and all other times do not increase if a landing zone resource is available. If one is not available, aircraft and cargo utilization time increases as these elements are awaiting a resource required to move on in the defined path. The output of this block is that the aircraft is in position to land where cargo can be unloaded.

The process continues with the Aircraft Lands action. To land, an aircraft must have arrived on station and a landing zone resource must be available. Aircraft and cargo times are not increased during this block as this is a common action to all methods. The output of this block is that the aircraft and its cargo are on a landing zone and able to be unloaded.

The next step is Unsecure Cargo. In this block, the cargo is unsecured from the aircraft and is able to be unloaded. This block requires the previous blocks to be completed and a manpower resource available to perform the action. During this block, the aircraft and its cargo are a single unit and their times increase together. At the completion of this block, the cargo is able to be unloaded from the aircraft and the manpower resource is released back to the manpower pool.

The process continues with the Unload Cargo block. To begin this block, the aircraft must have landed and cargo is unsecured. At this point, the model begins to track pallets instead of aircraft. During this block, aircraft utilization, cargo time, and manpower requirements increase. Manpower is required to unload cargo; the amount depends on the method being modeled. Upon completion of this block, cargo is off the aircraft, aircraft time stops, and the aircraft is able to perform other actions. Cargo is still in the transfer process so its time continues to increase. Once the cargo is removed from the aircraft and is at a staging point, the block is complete and the manpower resource is released.

The following step is Transfer to Intermediate Movement Resource. For an EFSS resupply load, this resource would most likely be an ammunition trailer; other cargo loads will require other assets. For this process to begin, the cargo must have been unloaded from the aircraft. During this process, a manpower resource is required as well as an intermediate mover. The values that increase are cargo time and manpower utilization. At the completion of this block, the manpower resource is released but the intermediate movement resource continues to be used. It must be noted that the time for this action is zero for the XRP as it is not required given the stated range of the cargo moving assets.

Next, either the XRP or the ammo trailer transfer the cargo in the Move to Gun Position block. Prior to commencing this step, the cargo must either transfer to an Intermediate Mover block or the cargo is moved by an XRP. During this step, the cargo time increases, but no other manpower resources are utilized; the ammo trailer resource time increases as the ammo trailer is in use for this block. The output of this step is that cargo is at its desired destination such as a gun position.

The endpoint of the model is the Cargo Arrives at Destination block. This step requires that the previous block be completed and a manpower resource be available. Cargo time, a manpower resource, and an ammo trailer resource utilization increase during this step. At the conclusion of this block, the model releases all resources and all time measurements stop increasing because the cargo has completed its journey.

E. OUTPUT ANALYSIS

We obtained outputs for 12 unique situations: loading and unloading the aircraft, two aircraft types, and three separate methods for moving the cargo. For each one of these situations, we completed 100 individual runs to gather statistically relevant data and to fully capture the effects of the variability inherent to the process. Table 8 presents the means and standard deviation for each situation.

Table 8. Model Results for All 12 Situations

Load / Unload	Method	Aircraft	Mean time (minutes)	Standard Deviation
Load	**WP**	**CH-53**	693.5	39.20
Load	**WP**	**MV-22**	273.3	17.33
Load	**XRP**	**CH-53**	47.1	2.78
Load	**XRP**	**MV-22**	47.4	3.04
Load	**MHE**	**CH-53**	118.7	6.75
Load	**MHE**	**MV-22**	51.3	3.01
Unload	**WP**	**CH-53**	628.5	41.81
Unload	**WP**	**MV-22**	256.3	16.99
Unload	**XRP**	**CH-53**	48.0	2.75
Unload	**XRP**	**MV-22**	47.8	2.47
Unload	**MHE**	**CH-53**	52.6	5.50
Unload	**MHE**	**MV-22**	30.6	2.00

The team performed a statistical analysis to determine if there was a statistically significant difference between the methods of moving cargo. We completed the analysis by assessing the outputs of the XRP runs against the working party and MHE in separate *t*-tests. All tests used an alpha value of 0.05, representing a 95% confidence band. All of the *t*-tests performed resulted in a rejection of the associated null hypothesis in that the means were from the same population. Histograms of the outputs of the model are detailed in Appendix C. The *p*-value results of these eight comparisons are shown in Table 9.

Table 9. *p*-value Results of Single-tail *t*-test Comparisons

	XRP vs. Working Party	XRP vs. MHE
Unload MV-22	$4x10^{-113}$	$1x10^{-116}$
Unload CH-53	$4x10^{-116}$	$6x10^{-12}$
Load MV-22	$2x10^{-117}$	$9x10^{-18}$
Load CH-53	$1x10^{-123}$	$3x10^{-125}$

The team performed an additional analysis after the simulation was complete to factor in the different carrying capacities of each method, as shown in Figures 18 and 19. Each figure captures the time in minutes to move 1,000 lbs. in the load or unload scenario. This analysis captured the impact of the carrying weight of the XRP of 2,756 lbs. when compared to the CH-53 pallet weight of 10,000 lbs. and MV-22 pallet weight of 4,000 lbs. The results are for each scenario and do not capture the flight time associated if additional sorties are required. The flight time associated with additional sorties is mission dependent and outside the scope of this effort, but would increase by approximately a factor of four when using the XRP instead of a fully loaded CH-53. Applying this analysis and the results shown in Table 8, the team identified a clear benefit of the XRP when a total cargo load is less than the carrying capacity of the XRPs loaded into the aircraft as part of a single sortie.

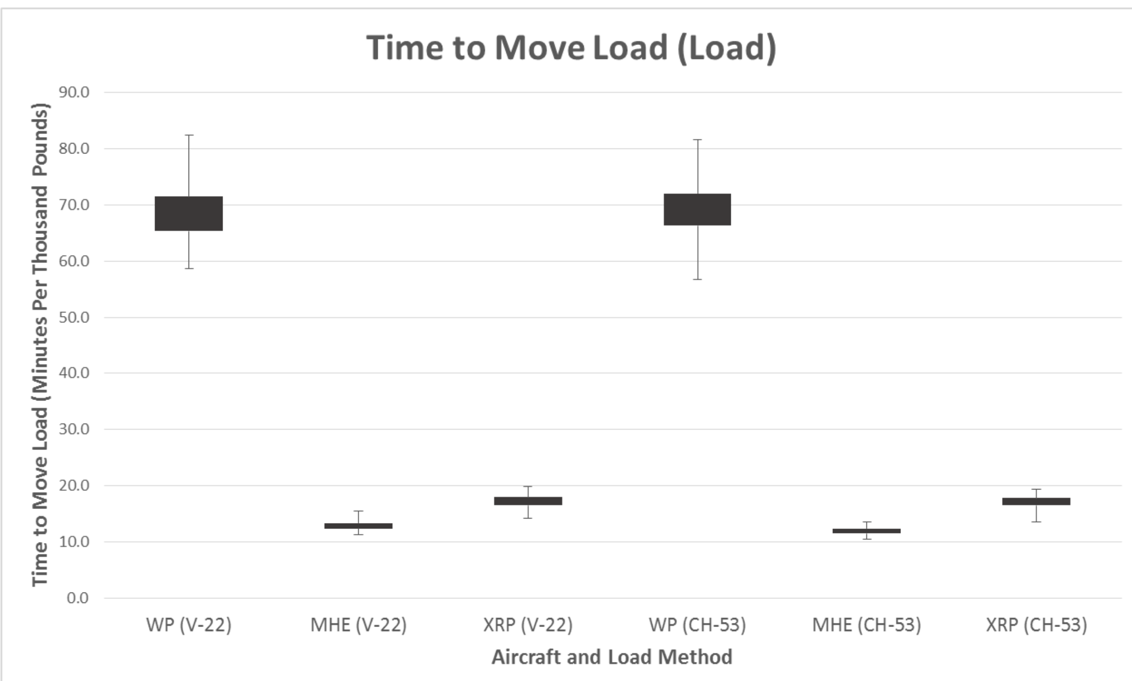

Figure 18. Normalized Time to Move (Load)

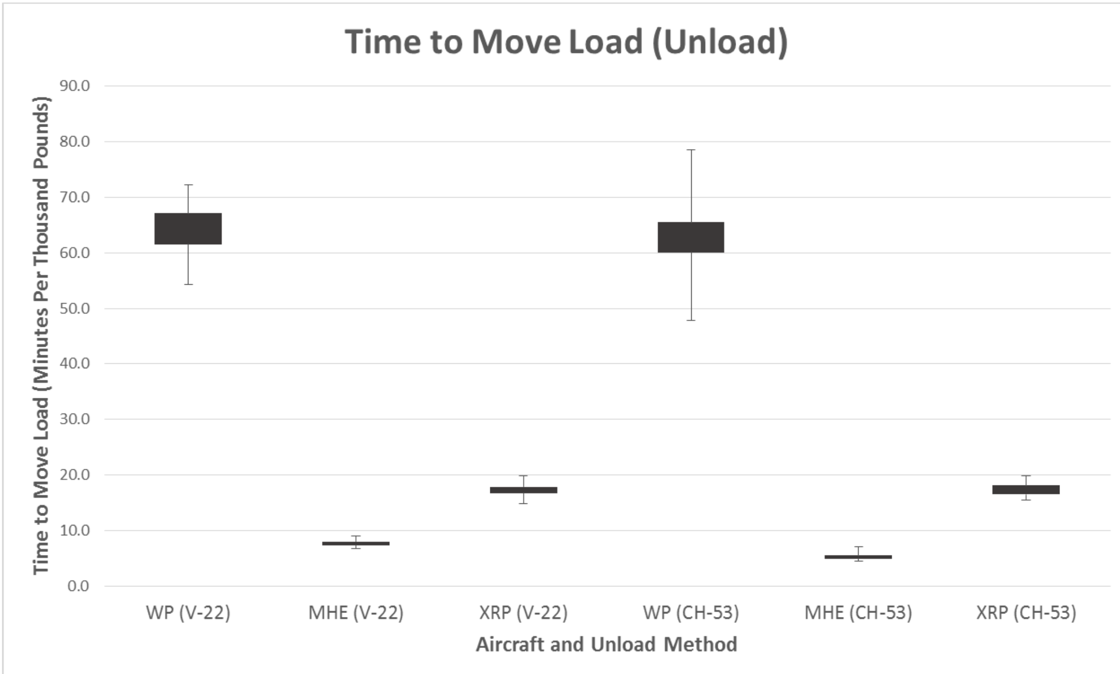

Figure 19. Normalized Time to Move (Unload)

The analysis must consider the amount of cargo an aircraft can carry on a single sortie for each method, as the XRP must be carried onboard the aircraft but the other two methods do not have to transport any cargo handling equipment. For the MV-22, analysis based on the values in Table 5 showed that an aircraft is able to transport only 5,512 lbs. of palletized cargo when using the XRP instead of 8000 lbs. with other methods. Similarly, as the CH-53 is likewise only able to transport two XRPs, the cargo capacity drops from 20,000 lbs., using the larger pallet size of the CH-53, to 5,512 lbs. of palletized cargo.

Because the XRPs are still under development, a complete and formal verification and validation of the model was not possible. Additionally, the project team was not able to obtain access to aircraft, MHE assets and qualified operators. To compensate for this lack of formal verification, and subsequent validation of the model, the inputs themselves were the focus of the verification efforts. We took inputs from verified and validated sources wherever possible as described in Tables 5, 6, and 7. We documented all assumptions so that if higher fidelity data becomes available in the future, the model and associated simulations could be re-run. The team also reviewed the results to ensure the model outputs were well behaved and in line with expected results based on the inputs. Therefore, we have high confidence in the model's outputs.

F. SIMULATION SUMMARY

Given the performance results alone, the XRP has an advantage in all scenarios with the exception of unloading an MV-22, where MHE proves faster. This assessment, based on a small working party, assumes that both MHE and XRPs are available. The team performed an additional analysis using the outputs of the simulation to help demonstrate the impact of the smaller cargo carrying capacity when using the XRP or MV-22.

Due to the reduced cargo carrying capacity of the aircraft when the XRP is used, moving the same amount of cargo requires four times as many sorties of the CH-53. For example, a sortie of two aircraft on a 30-minute round trip requires 480 minutes of flight time compared to 120 minutes of flight time for fully loaded CH-53s. Table 8 shows that the XRP can reduce the time moving cargo in the landing zone by tenfold when comparing the working party unloading a CH-53 and the XRP transporting the cargo, though the amount of cargo moved is reduced by almost four due to the weight limits for the XRP. The analysis shows the benefits of the XRP when the amount of cargo that needs to be transported is reduced, or when time spent manually moving cargo at a landing zone is not ideal. The tradeoff of the XRP becomes more difficult when factoring the cost of flight hours for the aircraft transporting cargo due to the additional sorties required to transport the cargo load.

V. LIFE-CYCLE LOGISTICS

A. LOGISTICS OVERVIEW

Like all ground vehicle programs in the Marine Corps, the XRP must meet readiness and sustainability goals that enable operational capabilities. To meet established XRP maintenance requirements, supportability must be designed into the XRP as part of the systems engineering process. As the XRP program transitions from the RIF contract and into Research, Development, Test and Evaluation, threshold and objective key performance parameters (KPPs) and key systems attributes (KSAs) must be written into the performance specification for maintainability. These KPPs and KSAs must address top-level maintenance requirements which are further decomposed into derived requirements and accompanying metrics for maintaining the XRP. Maintenance metrics must be traceable to user requirements and "derived from the system's operational requirements and expected use" and include availability, reliability, mean down time and ownership costs (Defense Acquisition University 2016d, 5.1.1.2). Maintenance metrics must be realistic, obtainable and verifiable. Unrealistic logistics and maintenance metrics will drive component and subsystem development and acquisition costs higher.

A total productive maintenance (TPM) approach should be incorporated into the XRP program "not only to prevent and correct equipment failures, but also to optimize equipment performance and extend equipment life cycle" (United States Marine Corps 2014b, 4). To achieve the goals of TPM and to meet XRP maintenance and reliability requirements, a system must be in place to predict, prevent, diagnose and correct failures. Developing a comprehensive maintenance system for the XRP will "shift maintenance from an unscheduled, reactive approach to a more proactive and prognostic approach" (United States Marine Corps 2014b, 5). The XRP logistics program may want to consider utilizing embedded sensors and diagnostic equipment integrated with the XRP's computer systems to collect and store information for recommended maintenance intervals.

As system information is collected and analyzed, EFSS units will have the ability to predict component and sub system failures of the XRP and perform preventive maintenance before these failures occur. By performing preventive maintenance at regular, predicted intervals, the operational availability of the XRP will increase, while reducing maintenance actions performed before they are required.

Preventive maintenance for the XRP requires training for the EFSS units to conduct routine Preventive Maintenance Checks and Services. Since the XRP is a new system, EFSS units need to be trained on what the common maintenance items are and how to identify when they need to be repaired or replaced. Some components of the vehicle are familiar to EFSS units, such as the diesel engine, and only require a technical manual. Other components, such as the automation and control systems, are less familiar and require more in-depth training.

Logistics maintenance for the XRP must be designed into the program on the front end in order to develop an effective TPM approach. Use of the RIF prototypes to gather reliability data and start developing maintenance procedures is recommended as the initial units are tested. Identification of maintenance personnel of similar systems is suggested to conduct a limited logistics demonstration to verify maintenance procedures of the XRP. A logistics demonstration can be a comprehensive event evaluating maintenance tasks critical to the system's operation (Defense Acquisition University 2016b).

B. LEVELS OF MAINTENANCE

Levels of maintenance within the Marine Corps are broken into three categories: organizational, intermediate and depot. The maintenance tasks at each level are determined by the "anticipated frequency of maintenance, task complexity, personnel skill-level requirements, special facility needs, [and] supply chain requirements" and are shown in Table 10 (Blanchard and Fabrycky 2011, 76).

Table 10. Major Levels of Maintenance. Source: Blanchard and Fabrycky (2011, 78).

Criteria	**Organizational Maintenance**	**Intermediate Maintenance**		**Supplier/Manufacturer/ Depot Maintenance**
Done where?	At the operational site or wherever the prime elements of the system are located	Mobile or semi-mobile units	Fixed units	Supplier/manufacturer/ depot facility
		Truck, van, portable shelter, or equivalent	Fixed field shop	Specialized repair activity or manufacturer’s plant
Done by whom?	System/equipment operating personnel (low-maintenance skills)	Personnel assigned to mobile, semi-mobile, or fixed units (intermediate-maintenance skills)		Depot facility personnel or manufacturer’s production personnel (high-maintenance skills)
On whose equipment?	Using organization’s equipment	Equipment owned by using organization		
Type of work accomplished?	• Visual Inspection • Operational checkout • Minor servicing • External adjustments • Removal and replacement of some components	• Detailed inspection and system checkout • Major servicing • Major equipment repair and modifications • Complicated adjustments • Limited calibration • Overload from organizational level of maintenance		• Complicated factory adjustments • Complex equipment repairs and modifications • Overhaul and rebuild • Detailed calibration • Supply support • Overload from intermediate level of maintenance

Organizational tasks performed on the XRP would be conducted by the XRP operators or maintenance personnel (EFSS units) and consist of tasks such as “inspecting, servicing, lubricating, and adjusting, as well as the replacing of parts, minor assemblies, and subassemblies” (United States Marine Corps 2014b, 16). Example organizational preventative maintenance tasks specific to the XRP would include oil changes, oil and fuel filter changes, and other tasks that fall under inspect, service, lubricate and adjust. Preventive maintenance while the XRP is still at an operational state reduces the probability of failure.

Corrective maintenance tasks at the organizational level result from a failure of the XRP and require that the system be fixed in order to restore it to an operational state.

At the organizational level, these tasks are limited to the replacement of parts, minor assemblies and subassemblies.

Intermediate maintenance is more technical than organizational maintenance and "may require a higher level of technical training, specialized tools and/or facilities" (United States Marine Corps 2014b, 16). The XRP is not anticipated to require additional or specialized facilities. The logistics footprint of the XRP will be limited to additional diagnostic software loaded onto existing maintenance computers and potentially a small selection of specialized hand tools. Stratom is designing the XRP so that it can be maintained and repaired using common tools already in the Marine Corps inventory (Stratom 2015). Intermediate maintenance is capable of performing repair, modification and fabrication of components and subsystem of the XRP, to include "calibration and repair of Test, Measurement and Diagnostic Equipment, software maintenance, precision machining, welding, evacuation, disposal, salvage, and demilitarization of equipment or materiel" (United States Marine Corps 2014b, 16). Preventive maintenance of the XRP would be calibration, test and diagnostics of the electronics systems, while corrective maintenance would be repair or system replacement beyond the scope and capabilities at the organizational level.

Depot level maintenance of the XRP is any maintenance task that is beyond organizational and intermediate level maintenance capabilities. An analysis of alternatives (AoA) should be conducted by the program office to determine whether to use contractor logistics support (CLS) or organic depot level support for the XRP. The complexity of the navigation, proximity sensors, autonomous, communications and other electronics systems, will likely drive the program to use CLS for depot level maintenance. For the purposes of this paper, we have assumed CLS for depot level maintenance.

Early contractor support for the RIF and prototype units is anticipated for all levels of maintenance. Maintenance data should be collected during these stages of the program and used in the AoA to determine the appropriate mix of organic and CLS maintenance. The AoA should include, but not be limited to, the following considerations (United States Marine Corps 2000, 4–5):

1. Operational readiness and support during deployment
2. Requirements for technical information
3. Requirement for support equipment
4. Cost and availability of repair and spare parts
5. Cost, schedule and performance
6. Density of equipment and geographical dispersion
7. Training systems and support training
8. Personnel skills required
9. Impact on force structure
10. Maintenance levels required
11. Commercial obsolescence
12. Planned life cycle
13. Facilities

C. XRP SUBSYSTEM DESCRIPTIONS

The XRP is composed of multiple subsystems, shown in Figure 20, which were integrated to create the completed XRP system.

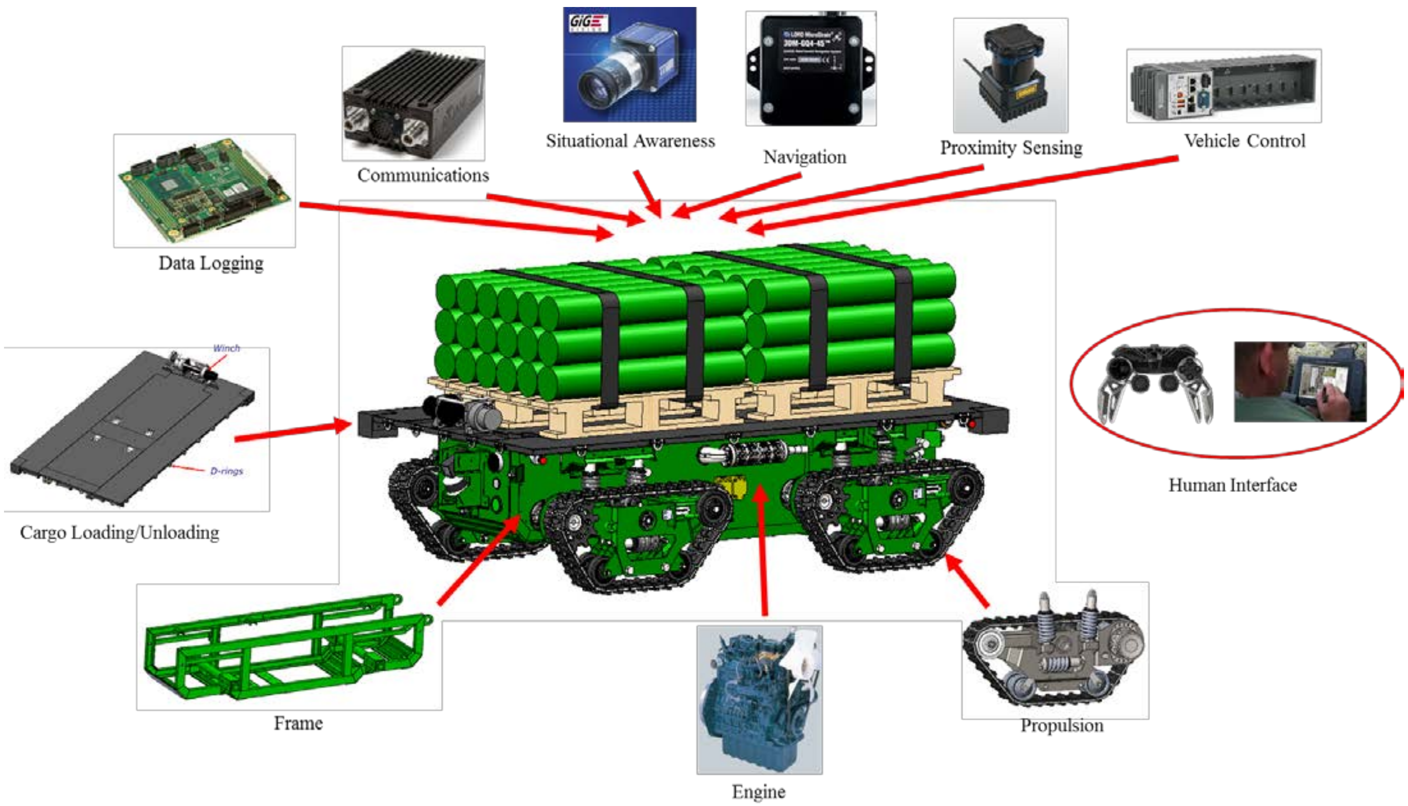

Figure 20. Major XRP Subsystems. Source: Stratom (2016).

1. Frame

The XRP frame is the main supporting structure to which all other components and subsystems are attached. The frame carries and distributes the weight of the cargo loaded onto the XRP.

- Organizational maintenance is limited to inspection, lubrication and replacement of minor assemblies that may be part of the frame.
- Intermediate maintenance would involve machining or welding of the frame in the event of minor damage.
- Depot level maintenance of the frame would require shipment of the XRP system back to the manufacturer. A bent frame or other major frame damage would require depot maintenance.

2. Power and Engine

A commercially available Kubota D902-E4B diesel engine provides the XRP vehicle propulsion and power generation.

- Organizational maintenance of the diesel engine would involve inspection and lubrication of the engine, as well as oil, oil filter, fuel filter, air filter and coolant changes. The replacement of fan belts and other small bolt-on items could be accomplished at the organization level.
- Intermediate maintenance should be capable of specialized preventive and corrective maintenance of the diesel to include all external components that cannot be repaired at the organizational level. These types of repairs would include maintenance to the starter, alternator, fuel pump, fuel injectors and other systems above the organizational level.
- Depot level maintenance on the diesel engine would include all internal systems, and includes pistons, crankshafts, connecting rods, and valve train. CLS is recommended for depot level maintenance.

3. Propulsion

The XRP propulsion system consists of the suspension, tracks and hydraulics and is used to move the vehicle during aircraft loading and unloading, as well as providing ground clearance.

- Organizational maintenance of the propulsion system would involve tasks such as inspection and lubrication of the propulsion system, and checking and maintaining the correct hydraulic fluid levels. Stratom is investigating the availability of commercial tracks for use on the XRP (Stratom 2016).

- Intermediate maintenance would involve replacement or repair of major propulsion subsystem not maintainable at the organizational level, such as the tracks. Tracked vehicles are widely used in the Marine Corps with mechanics possessing the ability to maintain the XRP.

- Because the Marine Corps has mechanics capable of maintaining tracked vehicles, no depot level maintenance is envisioned. Any maintenance beyond organic capability at the organizational and intermediate levels would require CLS.

4. Cargo Loading/Unloading

The cargo loading and unloading for the XRP consists of a top plate, winch, hydraulic lift cylinder and D-rings for loading, unloading, and securing cargo. The top plate may be swapped to provide other custom mounts for carrying cargo (Stratom 2015).

- Organizational maintenance of the cargo loading and unloading subsystem would consist of inspection and lubrication of components and maintaining the hydraulic fluid level of the lift cylinder. The winch and winch cable can be replaced at the organizational level should they become frayed or broken. The top plate can also be replaced at the organizational level.

- Intermediate maintenance of the cargo loading and unloading subsystem would involve welding of the D-rings, repair of the top plate, and repair or replacement of the hydraulic cylinder.

- No depot level maintenance is envisioned for the cargo loading and unloading subsystem, however any repairs required beyond organizational and intermediate maintenance would require CLS.

5. Vehicle Lighting

Lights are used on the exterior of the XRP in order to illuminate the ground and allow operation of the vehicle at night.

- All vehicle lights, fixtures, and connections should be inspected and replaceable at the organizational level.

- Vehicle lighting which cannot be maintained at the organizational level shall be able to be completed at the intermediate level. Intermediate tasks may include replacement of fixtures or wiring, or repair of wiring and connections.

- No depot level maintenance of the lighting system is envisioned for the XRP.

6. Computer and Software Intensive Subsystems

These subsystems all share a common maintenance plan due to their complexity. These subsystems are: vehicle control, data logging, communications, navigation/localization/proprioceptive sensing, proximity sensing, situational awareness, assist – sensing, low-level software architecture, autonomy, and robotic functionality. The vehicle control subsystem consists of a single Vehicle Control Unit computer. The data logging subsystem consists of a data logging computer that uses volatile memory for short term storage and non-volatile memory for long term storage. The communications subsystem consists of a Curtiss-Wright rugged 20-port network switch and a Rajant ME4 multiple-input and multiple-output Radio. The navigation/localization/proprioceptive sensing subsystem consists of an Inertial Navigation System, a RADAR True Ground Speed Sensor, wheel resolvers, microelectronic mechanical systems tilt sensors and other inertial, magnetic and global sensors. The proximity sensing subsystem consists of two line-scan Light Imaging, Detection, and Ranging (LIDAR) for the left and right sides of the vehicle with two sets of ultrasonic sensors to detect the front and rear of the vehicle. Tactile sensors are located at the four corners of the vehicle. The situational awareness subsystem consists of a Matrix Vision myBlueFox Wide Dynamic Range GigE Camera and an autonomy processor. The assist – sensing subsystem uses the high-level processor from the situational awareness subsystem in conjunction with its own dedicated 3D LIDARs mounted at the front and rear of the vehicle. The common maintenance plan for all of these subsystems is as follows:

- The computer and software intensive subsystems can be physically inspected and checked for proper operation at the organizational level.
- Software updates would be applied at the intermediate level.
- No depot level maintenance is envisioned for the computer and software intensive subsystems, however any repairs required beyond organizational and intermediate maintenance would require CLS.

7. Human Interface

The XRP human interface consists of a tablet or large phone and a joystick to allow the operator to monitor the XRP when operating autonomously or to control it when it is not operating autonomously.

- Functional checks and inspections at the organizational level can be conducted to ensure proper operation of the human interface with the XRP. There are no parts that may be repaired, so in the event of a failure, the components of the human interface can be swapped out and replaced at the organizational level.
- Software updates would be applied at the intermediate level.
- In the event of a failure, the components of the human interface will be returned for depot level maintenance or replacement.

D. MAINTENANCE AND SUPPORT INFRASTRUCTURE

The logistics and maintenance support infrastructure for the XRP must be traceable to the system level requirements, which are then decomposed "into the requirements for the support infrastructure, which, in turn lead into the requirements for the various elements of support" (Blanchard and Fabrycky 2011, 528). The elements of support should have specific design requirements that support meeting the top-level system requirements. These requirements must be quantifiable and testable in order to verify that the maintenance elements support the system requirements. There are seven elements of support that pertain directly to maintenance of the XRP. The PM should use the initial fielding of the XRP to validate the assumptions contained in the maintenance section

1. Supply Support

Supply support for the XRP must consider spares, repair parts, consumables, special supplies, software modules and the inventories required to maintain the XRP and keep it operational (Blanchard and Fabrycky 2011). The quantities of parts and consumables required to have on hand is dependent on the operational requirements desired by the XRP program office, parts failures, preventive and corrective maintenance actions, parts lead times and effectiveness of the inventory system. Considerations for repair parts and consumables in inventory at the organizational level are engine oil, oil filters, fuel, fuel filters, air filters, fan belts, hydraulic fluid, tracks, cables, light bulbs, coolant and lubricants. The XRP program office must determine and track these metrics in order to meet the desired operational requirements of the system.

2. Test, Measurement, Handling, and Support Equipment

The test and support equipment required for the XRP is dependent on the maintenance strategy and the tasks accomplished at each level of maintenance and will assist in diagnostics, calibration and performance of preventive and corrective maintenance of the XRP. The test and support equipment will assist the program office in collecting the metrics needed to determine if the requirements are being met, which include utilization rate, reliability, mean active corrective maintenance time, mean active preventative maintenance time, total maintenance downtime and mean time between maintenance (Blanchard and Fabrycky 2011). Considerations when determining the required test equipment are the item being returned to the shop for maintenance (XRP and its subsystem), the functions to be accomplished and the frequency of test functions (Blanchard and Fabrycky 2011). The program office must determine the electronic and mechanical test equipment, jigs, fixtures and maintenance stands required for maintenance of the XRP as well as distribution of equipment required for each level of maintenance (Blanchard and Fabrycky 2011). Recommended test equipment includes diagnostic laptop, data logging software and a diagnostic computer interface cable.

3. Maintenance Facilities

An analysis of the facilities required to support the maintenance of the XRP must be conducted. Due to the anticipated low density fielding of the XRP, use of existing facilities is desired. Factors to be considered for the XRP maintenance facilities include item turnaround time, facility utilization, energy utilization and facility costs (Blanchard and Fabrycky 2011).

4. Maintenance and Support Personnel

A manpower analysis should be conducted to determine the maintenance and support personnel required to maintain the XRP. The analysis should look at the maintenance tasks required and skill sets required to complete the tasks. The analysis will determine personnel quantities and skill levels, maintenance labor hours/maintenance action and personnel error rates required to maintain the XRP and meet the operational requirements determined by the program office (Blanchard and Fabrycky 2011). It is estimated that a single Marine can maintain multiple XRPs at the organizational level.

5. Training and Training Support

Training is an integral part of the XRP because it is necessary to familiarize the operators and maintainers (EFSS units) with the system as well as retain their proficiency utilizing the vehicle. To ensure that the training provided is effective, the frequency and duration of training should be tracked. Training data, per operator or maintainer, tracks whether the operators and maintainers are receiving too little, too much or just the right amount of training on the XRP. All of this training incurs costs for the program office, so tracking cost per person trained allows for better budgeting of future support costs. The anticipated low density fielding of the XRP will likely drive training to be conducted by the contractor at the contractor facilities rather than organically within the Marine Corps. A three day-long course for new equipment training for the XRP will initially be conducted, with the operators and maintainers conducting on-the-job training for future operators and maintainers. Operators and maintainers will also receive subsequent annual refresher training for three days, with different curriculums focusing on a specific job type.

6. Packaging, Handling, Storage, and Transportation

The XRP is material handling equipment. As such, it is designed for ease of transportation. The XRP is being developed specifically so that it can be certified for internal air transport aboard MV-22 and CH-53 aircraft (Stratom 2016). The XRP will be transportable by all common transportation modes used by the Marine Corps, including shipping, rail, and over-the-road trucking. The XRP will not require packaging material or shipping containers. It is designed to be easy to secure with multiple tie-down points using ratchet straps or chains. The XRP does not have any unique storage requirements beyond that of other diesel-powered vehicles.

7. Software Resources

Because of the automation and electronic subsystems of the XRP, there will be significant software requirements that must be considered early in the program. Requirements for software reliability and acceptable error rates must be determined, and metrics collected to verify that the requirements have been met. Software reliability can be measured as “the probability of failure-free operation of a software component or system in a specified environment for a specified time” and must be thoroughly tested prior to fielding (Blanchard and Fabrycky 2011, 524). The logistics software resource requirements should “include consideration of equipment, personnel, facilities, data, consumables and software” (Blanchard and Fabrycky 2011, 524). Due to the complexity of the software and sensors, it is anticipated that there will be bugs identified during RIF fielding. The required software updates will be handled by regular contractor software releases as required via gold disk push using the diagnostic laptop. Any software changes that impact the manuals or training material are the responsibility of the contractor to update.

THIS PAGE INTENTIONALLY LEFT BLANK

VI. LIFE-CYCLE COST ESTIMATE

A. OVERVIEW

Life-cycle cost consists of four major categories: research and development (R&D), production and delivery (P&D), operations and support (O&S), and disposal costs. The first step in creating a life-cycle cost estimate was tailoring a cost breakdown structure (CBS) specifically for this program.

“The cost breakdown structure links objectives and activities with resources and constitutes a logical subdivision of cost by functional activity area, major element of a system, and one or more discrete classes of common or like items” (Blanchard and Fabrycky 2011, 576). Figure 21 shows the tailored CBS of the XRP. Each category was broken down into smaller sections, or elements. An element is a minor cost component that is at a lower level than that of the category. Each element was carefully selected to ensure that all life-cycle cost activities of the XRP were identified and included in the CBS, and to ensure there was no overlap or double counting between elements. The categories helped in grouping common items and excluding others that are not similar. The elements also helped by providing granularity to what costs were included and were not included in each category.

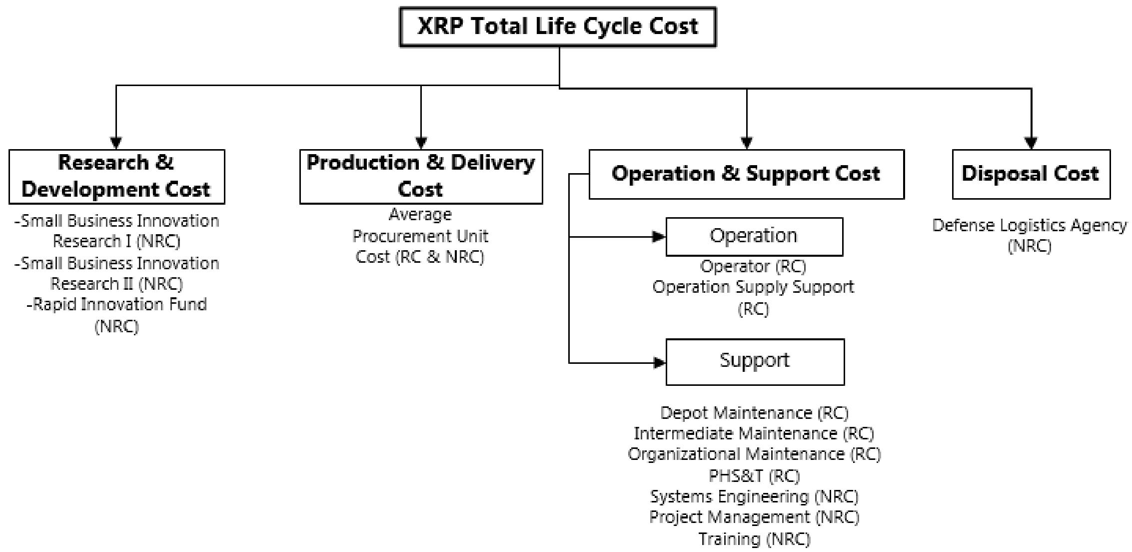

Figure 21. Cost Breakdown Structure of XRP.

1. Phase I: Research and Development Cost

The first costs to consider in the life-cycle cost of a system are in R&D. R&D is required when the system is unable to be procured as a commercial off the shelf item. Research costs are incurred through the "discovery of new knowledge, with the hope that such knowledge will be useful in developing a new product" (Loughran 2016). Development costs are incurred "when applying research results to the design for the new product" (Loughran 2016). The typical costs in R&D include trade studies, investigations, test and evaluation, prototyping, fabrication, applied research, and research laboratories.

The R&D cost of the XRP system was initially funded by the government's SBIR program to innovate a system that would autonomously transport cargo from either an MV-22 or CH-53 to an operational area (SBA 2016b). The "SBIR program is a highly competitive program that encourages domestic small businesses to engage in federal research (FR)/R&D that has the potential for commercialization" (SBA 2016a). Stratom was awarded the contract to develop the system. The R&D cost of that contract followed the set limits of the SBIR program's three phases:

> Phase I: The objective of Phase I is to establish the technical merit, feasibility, and commercial potential of the proposed FR/R&D efforts and to determine the quality of performance of the small business awardee organization prior to providing further Federal support in Phase II. SBIR Phase I awards normally do not exceed $150,000 total costs for 6 months.
>
> Phase II: The objective of Phase II is to continue the FR/R&D efforts initiated in Phase I. Funding is based on the results achieved in Phase I and the scientific and technical merit and commercial potential of the project proposed in Phase II. Only Phase I awardees are eligible for a Phase II award. SBIR Phase II awards normally do not exceed $1,000,000 total costs for 2 years.
>
> Phase III: The objective of Phase III, where appropriate, is for the small business to pursue commercialization objectives resulting from the Phase I/II FR/R&D activities. The SBIR program does not fund Phase III. Some Federal agencies, Phase III may involve follow-on non-SBIR funded R&D or production contracts for products, processes or services intended for use by the U.S. Government (SBA 2016a).

2. Phase II: Production and Delivery

P&D includes both recurring and non-recurring costs. Recurring costs are ongoing expenses that are required to produce and field the XRP systems. These costs are dependent on the number of XRP systems that are produced and delivered to the USMC. Non-recurring costs are a one-time expenditure and they are not dependent on the number of XRP systems produced. The USMC does not normally procure a system's bill of materials, lease or construct a production facility and then award a contract for integration support. For those reasons, the average procurement unit cost (APUC) was used to capture all of the production cost to reflect the most likely contract strategy. According to DAU, APUC includes "flyaway, rollaway, sail away cost (that is, recurring and nonrecurring costs associated with production of an item such as hardware/software, systems engineering (SE), engineering changes and warranties), plus the costs of procuring technical data (TD), training, support equipment, and initial spares" (Defense Acquisition University 2016a). Since APUC values for similar historic systems were readily available, the authors used those values as a basis for the P&D cost estimate for the XRP. APUC includes all reoccurring and non-reoccurring costs for production and can be multiplied by the number of XRPs that will be purchased to find total the P&D LCC. Finding APUC for XRP will be explained in P&D Estimate of Section B.

3. Phase III: Operations and Support

O&S is composed of sustainment costs incurred from the fielding of the system through its end of life and it includes all costs of operating and maintaining the entire fleet of XRP units. O&S includes both recurring and non-recurring costs.

a. Operation

- Operator: This element covers the fully burdened annual labor rate of the XRP operators.
- Operation Supply Support: This cost element covers fuel for the XRP during operational use.

b. Maintenance

There are three levels of maintenance: depot, intermediate and organizational. Each level will have labor, material, and overhead cost. These costs will differ within each level due to required skills and parts. The definitions below emphasize the cost aspect of maintenance. These definitions are consistent with those used in the logistics section even though they use different references.

- Depot Maintenance: "Depot maintenance is the cost of labor, material, and overhead incurred in performing major overhauls or other similar depot-level maintenance on a system or any of its major end items (e.g., aircraft engines) at centralized repair depots, contractor repair facilities, or onsite by depot teams" (Office of the Secretary of Defense 2014, 6–11). It also includes software resources, data logging and test equipment costs. This does not include handling, storage or transportation costs.
- Intermediate Maintenance: "Intermediate maintenance is the maintenance level between the most extensive maintenance—depot, and the least extensive (but usually the most common)—organizational" (Office of the Assistant Secretary of Defense for Logistics & Materiel Readiness 2015). This level of maintenance "Consists of the costs of labor, material, and any other costs expended at intermediate maintenance locations (such as Navy afloat or ashore Intermediate Maintenance" (Office of the Secretary of Defense 2014, 6–10).

- Organizational Maintenance: This is the most common minor maintenance that is "performed by a using organization on its assigned equipment. Its phases normally consist of inspecting, servicing, lubricating, and adjusting, as well as the replacing of parts, minor assemblies, and subassemblies" (Office of the Assistant Secretary of Defense for Logistics & Materiel Readiness 2015). This element includes the cost of labor, material, and overhead.

- Packaging Handling Storage & Transportation (PHS&T): The PHS&T cost element covers transportation, storage and handling costs. No special packaging is required for the XRP.

- Systems Engineering: This element covers the cost of the fully burdened annual labor rate for systems engineers. These in-service systems engineers assess "whether the fielded system and enabling system elements continue to provide the needed capability in a safe, sustainable, and cost-effective manner" (Defense Acquisition University 2016c).

- Project Management: This element covers the fully burdened annual labor rate of the PdM FSS management and staff.

- Training: This element covers travel cost for maintainers and operators. It also includes required training materials, facilities and manpower of trainers.

4. Phase IV: Disposal

> Disposal costs are the costs associated with demilitarization and disposal of a military system at the end of its useful life…. Costs associated with demilitarization and disposal include disassembly, materials processing, decontamination, collection/storage/disposal of hazardous materials and/or waste, safety precautions, and transportation of the system to and from the disposal site. Systems may be given credit in the cost estimate for resource recovery and recycling considerations (Defense Acquisition University 2016e).

The Disposal costs of the XRP will be negligible in comparison to the total life-cycle costs. Since the XRP has no known hazardous materials to dispose of, the main costs will be from PHS&T to Defense Logistics Agency (DLA).

B. XRP COST ESTIMATE

The total life-cycle cost estimate of the XRP system was broken down into the four phases. Inflation rates were based on the Naval Center for Cost Analysis (NCCA) joint inflation calculator (Naval Center for Cost Analysis 2016). The assumptions and their rationale for this cost estimate are as follows:

1. This cost estimate analysis was for a 10-year period based on the CDR recommendations.

2. This cost estimate analysis was for a quantity of 100 XRPs because of the size of the fleet per the CDR.

3. The base year for this cost estimate is fiscal year 2017 because that is when all cost information was prepared.

1. Research and Development Estimate

The total R&D cost of the XRP system has been established. The SBIR program funded Stratom approximately $2,787,000 to get the XRP to TRL 6 (Stratom 2016). MCSC funded Stratom $2,850,000 through the RIF, to obtain a TRL 8 (Stratom 2016). The total R&D costs came to $5,637,000 with the assumption that Stratom will get the XRP to TRL 8 by late 2017. No further R&D efforts are expected after the conclusion of the RIF.

2. Production and Delivery Estimate

To obtain the total P&D cost, the APUC must be found and multiplied by the number of XRPs that will be purchased (100). Since the XRP is still in development, statistical methods were used to forecast P&D.

Historical costs of similar DOD automated cargo systems were used to forecast an acceptable APUC of the XRP. Historical cost can be plotted (against another variable) and used to establish a parametric equation that represents a unique curve. There were four similar DOD systems that are comparable to the XRP. These systems include the R-Gator, Squad Mission Support System (SMSS), Dexterous Manipulation System (dMan), and the Legged Squad Support System (LS3). Each of these robotic systems moves cargo for the warfighter either autonomously or by remote control. It was discovered that the production and delivery cost per unit was $350,000 for the R-Gator (McMahon 2010), $200,000 for the SMSS (Defense Update 2016), $200,000 for the dMan (Hstar Technologies 2016), and $100,000 for the LS3 (Greenberg 2011). One way to forecast the cost per unit of the XRP was to take the average of all four systems; which was $212,500. This number introduced uncertainty.

a. Cost Estimating Relationship

To get a better estimate with less uncertainty, a cost estimating relationship (CER) was established. "A Cost Estimating Relationship (CER) is a mathematical function that relates cost to one or more technical variables" (Anderson 2015, 3). The CER gave us a mathematical function to calculate the cost per unit based on a technical variable. One of the main functions of the XRP and the aforementioned similar DOD systems is to carry cargo; therefore, the cargo carrying weight was used as the technical variable to establish the CER.

Figure 22 displays the carrying weight versus unit cost. It shows that as the carrying weight increases, price increases as well. To forecast the unit cost of the XRP based on carrying weight, a mathematical equation must be obtained from the plot. Since a straight line cannot be drawn to connect all of the data points to obtain a typical $Y = Mx + b$ equation, statistical regression methods such as ordinary least squares and general error regression methods (GERM) are needed to get a best fit equation that minimize the error. It is best to consider GERM because it allows the freedom to model any functional form (Anderson 2015, 62).

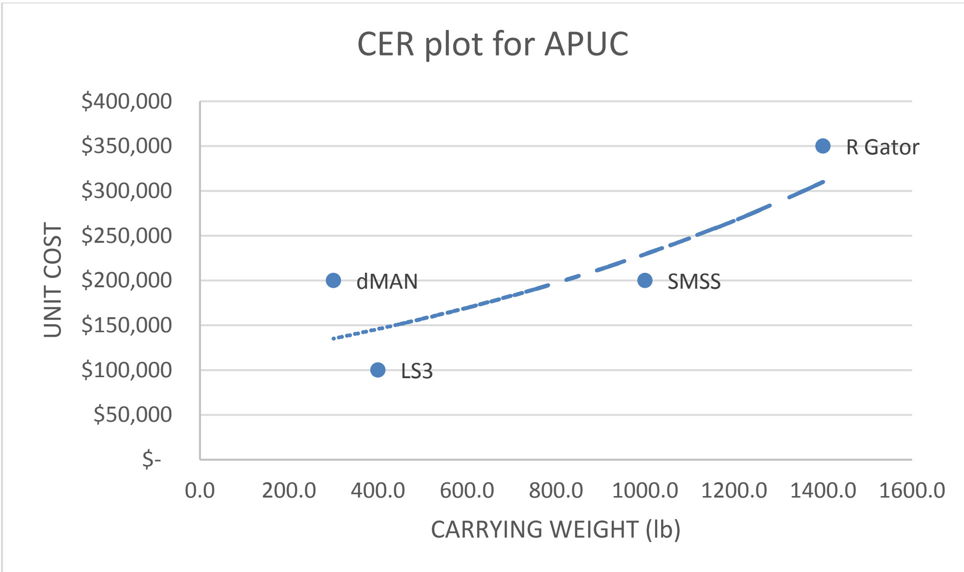

Figure 22. CER Plot of Similar Systems

b. General Error Regression Method

Deriving the CER equation from Figure 22 will induce error because it is a "best fit" representation of the historical data points. Statistically, these errors will follow either a multiplicative error or additive error seen in Figure 23. The additive error is seen as a uniform error, whereas the multiplicative error is seen as a growing error. To obtain the CER and minimize error, the GERM was used. "General error regression separates the question of whether estimating errors should be additive or multiplicative from the question of whether the shape of the CER should be linear or non-linear" (Anderson 2015, 62). A linear CER has a predictable form (e.g., $Y=Mx+b$), but a non-linear CER line can take any form. GERM allows us to obtain a CER from any model, regardless of form.

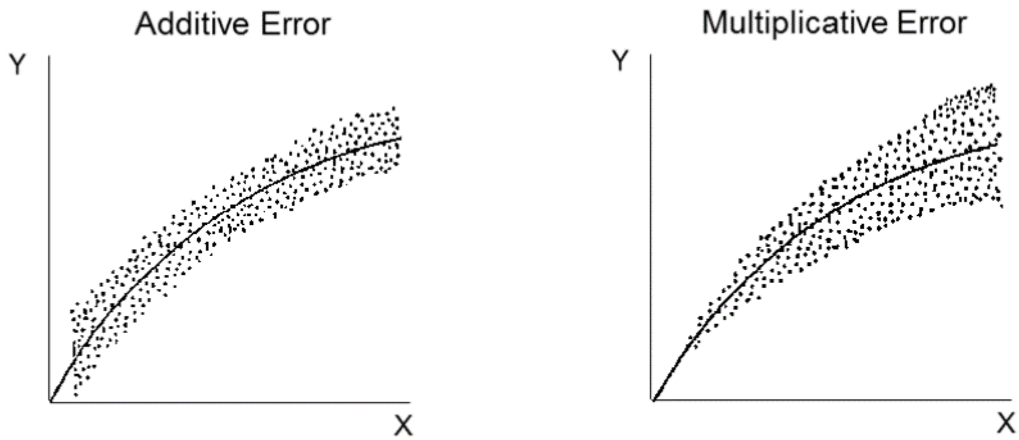

Figure 23. Error of Estimation. Source: Eskew and Lawler (1994).

GERM minimizes the error within the CER using numerical optimization techniques (Anderson 2015). GERM gives us a best fit equation for our historical data points. Since Figure 22 displays a non-linear CER, GERM gives us the equation in the form of:

$$Y = a + bx^c$$

a, *b*, and *c* are constant coefficients derived from historical data (Anderson 2015). *a* is the Y-intercept, *b* is slope of the regression line, *c* determines the shape of the curve and x is the cargo carrying weight, the independent variable. The authors inserted historical data of similar cargo systems into the GERM analysis tool, an Excel tool from NPS (Anderson 2015). The Excel tool calculates the standard error of each historical data point (cost versus weight), takes the sum of these errors, and then uses the Excel embedded "Solver" to minimize the standard error between the points giving the equation:

$$Cost = (5.7 + 17 \times (Carrying\ Weight)^{0.39}) \times 1000$$

Inserting the carrying weight of the XRP (2756 lb) into this equation results in a unit production cost estimate of $379,086, for a P&D total of $37,908,581 for a fleet of

100 XRPs. This estimate is better than taking the average of the four systems ($212,500) because it gives us a cost based on a technical variable.

Regression diagnostics are required to assess the quality of the model generated using GERM. Specifically, the coefficient of determination (typically denoted as R^2) can be used to quantitatively assess the quality of the model fit. Hayter defines the coefficient of determination as, "the proportion of the total variability accounted for by the regression line" (Hayter 2006, 573). In this case the calculated R^2 value is 0.59, which suggests that the regression line presented in Figure 22 accounts for 59% of the total variation in the data. While a larger R^2 value is certainly preferable, the team felt that the utilization of the cost estimate generated through GERM, despite the somewhat low R^2 value, was preferable to a purely historical based estimate. The historical cost estimate may be influenced by factors unrelated to the technical characteristics of the system, while the GERM estimate can be traced directly to a technical variable (in this case, the carrying weight).

3. Operations and Support Estimate

O&S costs consist of sustainment costs incurred from the fielding of the system through its end of life, which includes operating and supporting all 100 fielded XRPs for 10 years (Stratom 2016). An inflation rate of 1.2% was calculated for every year until 2026 for every O&S cost element except for fuel; the inflation rate for fuel is at 2.5% for every year through 2026 (Naval Center for Cost Analysis 2016).

a. Operation

One of the main costs to consider in operation is the operator. It is assumed that a mission of a mile out and back at five days a week totals two hours. It is also assumed that there is one operator per XRP. A FTE will work 2080 hours a year (40-hour a week × 52 weeks). Thus, the annual operating hours for one XRP is 2 (operating hours) × 50 (weeks/per year) = 100 person-hours for each XRP. Thus, the total person-hours for the fleet is 100 person-hours × 100 XRPs = 10,000 person-hours per year which equals to 10,000 person-hours / 2,080 hours = 4.8 FTEs. E-3 Marines have the typical skill set level required for operating equipment. The fully burdened annual rate of an E-3 Marine is $51,074 (Under Secretary of Defense (Comptroller) 2016). The annual cost for the CBS operator element is 4.8 FTEs × $51,074 = $245,155. By using the calculated inflation rate of 1.2%, the total cost for the CBS operator element is $2,588,262 for 10 years.

Fuel cost is $2.75/per gallon (U.S. Energy Information Administration 2016). To find the fuel burn rate of the XRP it is assumed the XRP cruises at an average of 2800 revolutions per minute, which gives a specific fuel consumption of 0.42 lb/HP-hr. This corresponds to the engine running at 22 HP (Kubota Farm & Industrial Machinery Service 2012). By multiplying 22 HP by 0.42 lb/HP-hr gives a burn rate of 9.24 lb/hr. A gallon of diesel weighs 7.1 lb/gal, thus, the fuel burn rate of a Kubota engine is 1.3 gallons/hour ([9.24 lb/hr]/[7.1 lb/gal]). It is assumed that each XRP will run a mission of one mile out and one mile back five days a week. At a speed of five miles per hour, the XRP will cover that weekly distance in 2 hours. The weekly number of gallons of burned fuel per XRP is 1.3 gallons / hour × 2 hours/workweek = 2.6 gallons/workweek. The number of gallons of burned fuel per year is: 2.6 gallons/workweek × 100 systems × 50 workweeks/year = 13,000 gallons/year. Fuel cost for the first year is $2.75/gallon × 13,000 gallons/year = $35,750/year. By using the inflation rate of 2.5% for fuel, the total cost for fuel is $400,521 for 10 years (Naval Center for Cost Analysis 2016).

b. Maintenance

Depot maintenance: It is assumed that the depot level maintenance facility will be in Boulder, Colorado because Stratom already has a facility there. It is assumed the cost for the depot level maintenance material included software resources, test equipment, data logging and Kubota diesel engines. It is also assumed that the XRP will need fewer person-hours for depot maintenance than a typical civilian sedan because it has fewer complicated subsystems. The depot level maintenance facility is $52,650 for the first year based on a facility of 5000 square feet at a rate of $10.53 per square foot per year (Loopnet 2016). By using the calculated inflation rate of 1.2%, the cost of depot level maintenance facility was $555,860 for 10 years.

The navigation system will last no less than 10 years. "The receiver shall have a service life of not less than 10 years when operated within any combination of the operational and environmental conditions specified herein, and with the following usage constraint:

1) On time of not more than 12 hours per day

2) Set-up data (Host Entered &/or Host Selected) changes no more than 2500 times.

3) There are no more than 4 key loads per day.

4) Storage device survives a minimum of 10000 erase cycles" (Rockwell Collins 2012).

Since the XRP will not be operating more than 12 hours a day, it is expected that the navigation system will last more than 10 years and therefore no replacement will be needed (i.e., no cost added).

The cost for depot level maintenance material (software resources, data logging, and test equipment) in Table 11 is $28,846 for year one, $6,914 for year four, $7,081 for year eight (engines are not included here due to their different maintenance interval). The depot level maintenance material cost is broken down for those specific years to align with the different service intervals for the listed material. The calculated inflation rate of 1.2% is taken into account for all years. A quantity of two sets of software resources, data logging, and test equipment for 100 XRPs is assumed because a spare is required if one set were to become inoperable. The total cost is $21,061 for 10 years. The assumption is that the engines will not have to be replaced because the total calculated operation hours for each XRP engine for 10 years is 1,000 hours. The Kubota engine manual supports an engine lasting over 3000 hours (Kubota Farm & Industrial Machinery Service 2012). Although engines can last over 3000 hours, re-build kits will be used for unexpected failures. Rebuild kits provide the necessary parts for repairable engines. Using the reliability equation estimate based on a MTBF of 3,000 hours and a mission of duration of 1,000 hours, $R = e^{-K\lambda t} = e^{-t/M} = 0.71$ or 71% where t = time, M = MTBF = $1/\lambda$, $K = 1$ and R = reliability (Blanchard and Fabrycky 2011, 518). Each kit costs $751 (Kumar

Bros USA 2012). Therefore, 29 kits (100 kits – 71kits) will cost $21,779. The total cost for depot level maintenance material is $21,779 (kits) + $21,061 (all other) = $42,840.

The median annual labor rate for an automotive service technician and mechanic is $40,160 (Bureau of Labor Statistics 2016). This amount is doubled to get the fully burdened annual labor rate of $80,320 (Nielsen 1997). There are 2,080 hours (40×52) in a typical work year. The fully burdened hourly labor rate is calculated as $38.62 ($80,320 / 2,080 hours). We can assume that the XRP will need fewer person-hours for maintenance than a typical civilian sedan which requires a total of 13 person-hours (a year) for all levels of maintenance (Owen 2016). Therefore, two person-hours were assumed per XRP for depot level of maintenance. The total person-hours are 200 (2 hours × 100 XRP) for the entire fleet for year one. The first year cost is $38.62 × 200 = $7,724. By using the calculated inflation rate of 1.2%, the total cost for depot level maintenance labor is $81,547 for 10 years.

The total depot maintenance cost element was calculated by adding $555,860 (facilities) + $42,840 (material) + $81,547 (labor) = $680,247.

Table 11. Depot Level Maintenance Parts

Depot Level Maintenance Parts							
Service Intervals	**Parts,Qty & unit price**	**First-Year Cost**	**Year 4**	**Year 8**	**Total cost (10 years)**	**Source for Cost**	**Source for service interval**
1,000,000 hrs	**Solid State Drive (Qty 2 @ $158 per unit)**	**$316**			**$316**	**(Newegg 2016)**	**(What Digital Camera 2016)**
4 years	**Dell 12 Rugged Laptop (Qty 2 @ $3,319 per unit)**	**$6,638**	**$6,798**	**$6,962**	**$20,399**	**(Dell 2016)**	**(Computer Hope 2016)**
4 years	**USB PC Interface Cable Qty 2 @ $56 per unit)**	**$113**	**$116**	**$118**	**$347**	**(Scuba 2016)**	**Assumption: New cable for new laptop**
N/A	**Overhaul d902 Kubota Rebuild kit (Qty 29 @ $751 per unit)**	**$21,779**			**$21,779**	**(Kumarbrosusa 2012)**	**N/A**
Total		**$28,846**	**$6,914**	**$7,081**	**$42,840**		

Intermediate maintenance: There is no intermediate-level maintenance facilities cost in this estimate because although intermediate facilities do exist, all the intermediate-level work on the XRPs will be performed in the field. One of the assumptions is to use a mix of E-5, E-6, E-7, E-8 and E-9 Marines for this level of maintenance because those are typically the skill sets that are found in this level of maintenance. The annual fully burdened rates are (Under Secretary of Defense (Comptroller) 2016):

E-9: $153,228

E-8: $121,652

E-7: $108,115

E-6: $94,202

E-5: $75,906

An assumption is that a typical shop would include one E-9, one E-8, one E-7, two E-6s, and three E-5s. An average annual fully burdened rate for the entire shop is calculated by adding the individual burdened rates of each member and then dividing by the total number of people in the shop. This is calculated to be \$99,890 (\$799,117 / 8). The average labor rate for one person-hour within the shop is \$99,890/2,080 (hours in a year) hours = \$48.02. Three person-hours per XRP was assumed for this level of maintenance. The total person-hours for the entire fleet are 300 person-hours per year.

By using the calculated inflation rate of 1.2%, the annual labor cost will be \$50.97 in year six, because intermediate maintenance will start in the sixth year. The total labor cost will be \$50.97 × 300 hours = \$15,291. The cost for intermediate maintenance material encompasses all maintenance from the six-year service interval, which is equal to \$8,446 per XRP in Table 12. The total material maintenance cost for the entire fleet is therefore \$844,600 for year six. The total cost of the intermediate maintenance is \$844,600 (material) + \$15,291 (labor) = \$859,891.

Table 12. Intermediate Level Maintenance Parts

Intermediate Level Maintenance Parts					
Service Intervals	**Parts,Qty & unit price**	**Year 6**	**Total cost (10 years)**	**Source for Cost**	**Source for service interval**
6 years	**Boxer 320 Mini Skid Steer (Qty 4 @ \$1,450 per unit)**	**\$6,156**	**\$6,156**	**(Tornado Parts 2015)**	**(Stratom 2016)**
6 years	**Toro Track Rubber (Qty 4 @ \$539 per unit)**	**\$2,290**	**\$2,290**	**(Weingartz Supply 2015)**	**(Stratom 2016)**
Total		**\$8,446**	**\$8,446**		

Organizational maintenance: There is no organizational-level facilities cost in this estimate because it is performed strictly in the field. Therefore, the costs associated with organizational maintenance are labor and material. One of the assumptions is E-3 Marines will be used at the organizational-level because they have the skill sets for this level of maintenance. We can assume that the XRP will need less person-hours for maintenance than a typical civilian sedan which requires a total of 13 person-hours (a year) for all levels of maintenance (Owen 2016). Therefore, five person-hours is assumed per XRP for organizational level of maintenance. The total person-hours for all 100 XRPs, is 500 per year. The hourly fully burdened rate for an E-3 is $24.55. The labor cost for the first year is $24.55 × 500 = $12,275. For 10 years with 1.2% inflation, the labor costs totals $129,595.

As seen in Table 13, maintenance parts for one XRP totals $6,065 (10-year period with 1.2% inflation).

Table 13. Organizational Level of Maintenance

Organizational Level Maintenance Parts														
Service Intervals (Hours if not noted)	Parts (Qty)	Unit Cost	First-Year Cost	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Total cost (10 years)	Source for Cost	Source for service interval
200	Oil (1 gallon)	$11		$174		$178		$182		$187		$720	(Walmart 2016a)	(Kubota 2016)
200	Oil Filter (1)	$10		$152		$155		$159		$163		$629	(Walmart 2016b)	(Kubota 2016)
400	Fuel Filter(1)	$19				$148				$155		$302	(Diesel Specialist 2016a)	(Kubota 2016)
500	Fan belt(1)	$26					$161					$161	(Diesel Specialist 2016b)	(Kubota 2016)
1 year	Air Cleaner(1)	$51	$51	$52	$52	$53	$53	$54	$55	$55	$56	$481	(Diesel Specialist 2016c)	(Kubota 2016)
2 year	Radiator hose(1)	$9		$9		$9		$10		$10		$38	(Madison Tractor Company 2014)	(Kubota 2016)
2 year	Radiator clamp(1)	$6		$6		$6		$6		$7		$25	(PartsTree 2014a)	(Kubota 2016)
2 year	Fuel pipe(1)	$10		$10		$10		$10		$11		$41	(AliExpress 2016)	(Kubota 2016)
2 year	Fuel clamp (1)	$1		$1		$1		$1		$1		$2	(PartsTree 2014c)	(Kubota 2016)
2 year	Radiator Coolant(1)	$8		$9		$9		$9		$9		$35	(Southeastern Equipment & Supply 2016)	(Kubota 2016)
2 year	Intake air line(1)	$61		$62		$64		$65		$67		$257	(PartsTree 2014b)	(Kubota 2016)
N/A	M8000 Self-Recovery Winch & Cable (Qty 4)	$843	$3,372									$3,372	(GoWarn 2015)	N/A
Total		$1,055	$3,423	$473	$52	$632	$215	$496	$55	$663	$56	$6,065		

For 100 XRPs this cost is $606,500. These materials include the oil, oil filter, fuel filter, fan belt, air cleaner. It is assumed that a quantity of four sets of winches and cables are procured during the first year for spares because the XRP is equipped with one set at the time of initial procurement. No replacement cost is expected for the winch and the

cable because of its lifetime warranty for mechanical components and the seven-year warranty for electrical components (Warn 2016). The organizational maintenance cost element can be calculated by adding $606,500 (material) + $129,595 (labor) = $736,095

PHS&T: It is assumed that storage space will be needed for the XRP. It also is assumed that 10 XRPs will be in storage at any given point in a year. The monthly storage fee is $70 per pallet (SPAWAR Atlantic 2016). The storage cost for the first year is $70 × 10 XRPs × 12 months = $8,400. The transportation and handling cost is $817 for a load size similar to that of the XRP (UsShip 2016). By doubling the transportation and handling cost to take into account that the XRP must return to the operators for use, the transportation and handling cost for one XRP is $1,634 and $163,400 for the fleet. One of the assumptions is that the XRP will only be shipped or transported once per year; therefore, the transportation and handling cost for the first year is $163,400. No special packaging is required for the XRP, thus the total transportation and handling cost is $171,800 for the first year. By using the calculated inflation rate of 1.2%, the total cost for the PHS&T element is $1,813,804 for 10 years.

Systems Engineering: It is assumed six GS-13 federal employees at step 10 for systems engineering support are required because of the fleet size of the XRP. The annual labor rate of a GS-13 federal employee at step 10 is $96,004 without locality increases (OPM 2016). The fully burdened annual labor rate is twice the annual labor rate (Nielsen 1997). Therefore, the fully-burden annual labor rate is $192,008. The total cost for the first year is $1,152,048. By using the calculated inflation rate of 1.2%, the total cost for the systems engineering element is $12,162,917 for 10 years.

Project management: The annual labor rate of a GS-14 federal employee at step 10 is $113,444 without locality increases (OPM 2016). Therefore, the fully burdened annual labor rate is $226,888. The total cost for project management is $1,361,328 for the first year for six FTEs. Six FTE's are required for the entire program of this size. By using the calculated inflation rate of 1.2%, the total cost for the project management CBS element is $14,372,422 for 10 years.

Training: It is assumed annual training for operators and maintainers will take place at a government facility in Quantico, VA for a period of three days per year, excluding travel time, for every trainee. It is reasonable to assume Quantico, VA as the training location because they can be trained in an operationally realistic environment. A training duration of three days is reasonable because of the number of subsystems in the XRP. The per diem rate is $142 per person for Stafford, VA (Defense Travel Management Office 2016) and the per diem rate includes lodging, meals and incidentals. It is assumed Marines will be coming from Camp Pendleton, CA because it is the furthest location CONUS. A round trip commercial flight from Santa Ana, CA to the District of Columbia metropolitan area cost is $843 per person (United Airlines 2016). The cost for a rental economy car is $198 for five days at Reagan National airport (Enterprise 2016). The total travel cost for the first year for 35 trainees is [$142 × 5 days (including travel days) + $843 + $198] × 35 trainees = $61,285. By using the per diem, airfare and car rental costs, the total travel cost for all 35 trainees is $61,285 for the first year. By using the calculated inflation rate of 1.2%, the total travel cost for 10 years is $647,025. The median annual labor rate for a training and development specialist is $58,210 (Bureau of Labor Statistics 2016). The fully burdened contractor annual labor rate is twice that of the annual labor rate which equals to $116,420. One of the assumptions of this cost estimate is to use 0.5 FTE of the training and development specialist for all trainees per year. By using the calculated inflation rate of 1.2%, the total cost for trainer's labor is $614,561 for 10 years. By adding the travel and trainer's labor costs, the total cost for the training CBS element is $1,261,586 for 10 years.

By adding all of the cost elements in the O&S phase, the total is $34,875,746. Table 14 provides granularity for each of the cost element estimates.

Table 14. O&S Cost Breakdown

O&S Cost Breakdown of XRP			
Cost Element Description	Total Cost (including inflation)	Fully burdened annual labor rate	Year 1
Operations & Support			
Operation			
Operator	**$2,588,262**	**$51,074**	**$245,155**
Operation Supply Support (Fuel)	**$400,521**		**$35,750**
Support			
Depot Maintenance	**$680,247**		
Intermediate	**$859,891**		
Organizational	**$736,095**		
Packaging Handling Storage &Transportation (PHS&T)	**$1,813,804**		**$171,800**
Systems Engineering	**$12,162,917**	**$192,008**	**$1,152,048**
Project Management	**$14,372,422**	**$226,888**	**$1,361,328**
Training	**$1,261,586**		**$119,495**
Travel for trainees	$647,025		$61,285
Trainers (Contractor)	$614,561	$116,420	$58,210
O&S Total	**$34,875,746**		

4. Disposal Estimate

The Disposal costs of the XRP will be negligible in comparison to the total life cycle costs. Since the XRP has no known hazardous materials to dispose of, the main costs will be from PHS&T to Defense Logistics Agency (DLA). It is assumed the 100 XRPs are planned to be shipped from Quantico, Virginia to the DLA disposition center in Richmond, Virginia. The cost to ship 100 XRPs is $30,000 (10 Freight trucks × $3000 each freight truck; each freight truck can hold 10 XRPs), using standard freight shipping rates (UsShip 2016). Since Marine E-3s understand how to handle the XRPs, their support would be required to transfer the XRPs. This personnel support is $9,820 (10 Marines × 40 hrs. × $24.55). The XRPs are planned to undergo the disposal (reutilization, transfer and donation) process through the DLA, which is at no cost to the PdM. The estimated total disposal cost of the XRP is $39,820.

C. LCCE SUMMARY

The main costs to consider in the LCC estimate of the XRP system are the R&D, P&D, O&S, and Disposal costs. Table 15 shows the cost for all four of those phases. R&D costs include trade studies, test and evaluation, prototyping, fabrication, applied research, and research laboratories. The R&D costs of the XRP have already been established. Initially, the government's SBIR program, which followed set cost limits within the SBIR guidelines, funded R&D; the XRP is now funded by a RIF through MCSC (Stratom 2016). The total R&D cost for XRP is $5,637,000. For P&D, the APUC was found through a CER equation based on cargo carrying weight. The total P&D costs were found by multiplying the APUC by 100 XRP units for a total of $37,908,581. The O&S costs consist of sustainment costs incurred from the fielding of the system through its end of life, which includes operating, maintaining, and supporting all fielded XRPs. The O&S costs have been broken down in Table 14 and the total is $34,875,746. Since the XRP has no known hazardous materials to dispose of, the main disposal costs will be logistics support. The estimated disposal cost of the XRP is $39,820. Adding the costs of R&D, P&D, O&S, and Disposal the total LCC cost estimate for the XRP system is $78,461,147.

Table 15. Total Cost Breakdown of XRP

Total Life Cycle Cost Breakdown of XRP			
Cost Element Description	**Total Cost (including inflation)**	**Fully burdened annual labor rate**	**Year 1**
Research & Development			
SBIR Phase I (2011)	$100,000		
SBIR Phase II (2012-2013)	$937,000		
SBIR Phase II Ext (2013-2014)	$750,000		
SBIR PII Technology Development (2014)	$750,000		
SBIR PII Operational (2014-2015); TRL 6	$250,000		
Rapid Innovation Fund (2015-2017)	$2,850,000		
Subtotal	$5,637,000		
Production & Delivery			
APUC- includes drive away, rollaway, sailaway cost (that is, recurring and nonrecurring costs associated with production of an item such as hardware/software, systems engineering (SE), engineering changes and warranties), plus the costs of procuring technical data (TD), training, support equipment, and initial spares.	$37,908,581		
P&D Subtotal	$37,908,581		
Operations & Support			
Operation			
Operator	$2,588,262	$51,074	$245,155
Operation Supply Support (Fuel)	$400,521		$35,750
Support			
Depot Maintenance	$680,247		
Intermediate	$859,891		
Organizational	$736,095		
Packaging Handling Storage &Transportation (PHS&T)	$1,813,804		$171,800
Systems Engineering	$12,162,917	$192,008	$1,152,048
Project Management	$14,372,422	$226,888	$1,361,328
Training	$1,261,586		$119,495
Travel for trainees	$647,025		$61,285
Trainers (Contractor)	$614,561	$116,420	$58,210
O&S Total	$34,875,746		
Disposal			
Transportation	$30,000		
Personnel Suppot	$9,820		
Disposal Sub-Total	$39,820		
Logistics-relevant cost	$8,380,226		
Total	***$78,461,147***		

THIS PAGE INTENTIONALLY LEFT BLANK

VII. SUMMARY AND CONCLUSION

A. SUMMARY

This project examined the use of the XRP to move resupply cargo to and from an MV-22 and CH-53 in order to assess the potential benefits and impacts to the Marine Corps. Answering the set of questions summarized below supported this assessment.

Question #1: Which sizes and types of operations would benefit from a robotic pallet mover and which would not?

The operations that would benefit most from using the XRP are operations where an aircraft delivers less than a full load on a sortie. The model makes no distinction for the type of cargo, only the weight. The major drawback to using the XRP is the reduction in cargo capability due to the aircraft having to carry the additional weight of the XRP itself. There are two distinct situations where the limitation imposed on cargo size by the XRP will be offset: small loads and short flight times. If a cargo load is being delivered that leaves sufficient room in the aircraft to carry the XRP, then there will be no operational impact to carrying the XRP. Similarly, if a sortie is a relatively short flight time, then the time savings in loading and unloading will offset the additional flights required, especially when working parties are the method used to load and unload the aircraft.

Question #2: When is it better to load or unload using a working party of available Marines? When is it better to bring in and use MHE? In the operationally relevant scenarios when a robotic pallet mover is beneficial, what are the quantified benefits in terms of time, cost, and manpower? Do these benefits justify procuring robotic pallet movers?

The use of a working party of Marines significantly increases the time required to both unload and load cargo, so a working party is most useful in scenarios where time is not a critical factor. A working party is also not limited in terms of cargo weight, beyond the limitations of the aircraft or pallet, which becomes useful when it is desired that the aircraft is loaded to its capacity. A working party is also beneficial in difficult terrain where MHE or the XRP cannot traverse the terrain.

The modeling effort has shown MHE outperforms the working party in terms of time to load and unload the aircraft and outperforms the XRP in terms of the aircraft cargo carrying capacity. Therefore, in those scenarios in which MHE is available, it should be used. The benefit of using MHE diminishes when it is available for one part of the load or unload.

The benefit of the XRP is in its ability to quickly embark and debark from aircraft while it is fully loaded with cargo. This greatly reduces the time, when compared to a working party, that aircraft spend on the ground waiting for cargo to be loaded or unloaded. The XRP's range also reduces the time spent in vulnerable locations since it can be loaded and unloaded with cargo outside the landing zone and driven to or from the aircraft without an operational pause. The negative impact is the approximately 350% and 35% reduction in carrying capacity when compared to the CH-53 and MV-22 pallets, respectively. The reduced carrying capacity increases the number of sorties required by four when compared to the CH-53 and two when compared to the MV-22, to achieve the same cargo delivery weight, effectively increasing the flight time per aircraft by four and two, respectively. The benefits and impacts of the XRP, to include additional logistics support and life-cycle costs, require further analysis by the respective program office to determine if the procurement is justified.

Question #3: What is the anticipated logistics cost and footprint over the life cycle of the system?

The XRP is in the prototyping stage, presenting an opportunity for the program office to write appropriate requirements based on collecting relevant logistics data. Logistics must consider the seven elements of support and be traceable to the top-level system requirements. This report recommends a TPM approach for the XRP to maximize system reliability and availability and to predict required maintenance actions based on collected data. This report recommends an AoA considering personnel, training, facilities and cost to determine whether the XRP should be maintained entirely by organic support, or whether partial CLS support would be beneficial. If it is determined that partial CLS support should be adopted, the AoA can also investigate and recommend which maintenance actions are to be performed by which assets. The estimated logistic cost for the entire fleet of the XRP over its 10-year period was calculated to be $8,380,226 by including only the logistics-relevant cost elements of the O&S phase (Table 14), which are operator, operator supply support, depot maintenance, intermediate maintenance, organizational maintenance, packaging, handling, storage and transportation, and training. The entire disposal cost is also included.

B. CONCLUSION

The objective of this project was to quantify the potential benefits and impacts of the robotic pallet mover in an operational environment and present the results to the Marine Corps. Modeling and simulation permitted quantification of the use of the XRP in a variety of operationally relevant resupply scenarios. Given the performance results alone, the XRP has an advantage in all scenarios with the exception of unloading an MV-22, where MHE proves faster. Monte Carlo simulation and subsequent statistical analysis indicated the XRP outperforms working parties by an average of 225 minutes and outperforms MHE by four minutes to load two tons of cargo when using the MV-22. When using the CH-53, load time for the XRP is 645 minutes faster than using a working party and 72 minutes faster than using MHE to load five tons of cargo. When performing unloading operations using the MV-22, the XRP outperforms working parties by an average of 210 minutes and MHE outperforms the XRP by 18 minutes to unload two tons of cargo. When using the CH-53, the XRP outperforms working parties by an average of 580 minutes and MHE by five minutes to unload five tons of cargo. The benefits of the XRP are clearly shown when the amount of cargo that needs to be transported is reduced or when time spent manually moving cargo at a landing zone is not ideal. The tradeoff of the XRP becomes more difficult when factoring the cost of flight hours for the aircraft transporting cargo due to the additional sorties required to transport the cargo load.

In order to help the PdM FSS make near-term decisions as he works to transition the XRP from a RIF effort into a program of record, the authors performed a life-cycle cost analysis. The life-cycle cost consisted of four major categories: R&D, P&D, O&S, and Disposal costs. The estimated Life-cycle costs for a fleet of 100 XRPs is estimated to be $78,461,147. This cost includes research and development, production, operations and sustainment, and disposal.

In addition to the modeling and simulation analysis and the life-cycle cost analysis, this report reviewed requirements in depth. The results of both (1) the stakeholder needs analysis and (2) the review of TTPs provided additional insight when conducting the requirements review. The authors derived additional requirements based on this insight. Stakeholder needs analysis resulted in several key findings, which included the requirement to decrease load and unload times by 10% while not significantly increasing the maintenance burden on operators. The TTP review showed that some minor revisions to existing TTP will be required, mostly with regard to the safe use of a semi-autonomous vehicle. The XRP's interfaces with other fielded systems, specifically those dealing with dimensions, weight, battery, and fuel constraints are important because a noncompliance would result in the inability to be transported on the MV-22, CH-53 as well as other naval assets. Additionally, the requirements analysis provided recommendations for improving the wording of several ambiguous or conflicting requirements.

PdM FSS can use future experience with the units fielded via the RIF to validate the modeling and simulation results, gain more information on logistics impact, and refine system requirements described in this report. A thorough understanding of cost versus benefit is necessary before transitioning to a formal program of record.

C. FUTURE WORK

The intent of this paper is to provide data and analysis to inform future decisions regarding the XRP RIF program and any other effort seeking to transition similar autonomous cargo handling solutions. The analysis presented in this paper shows the XRP can accomplish loading and unloading tasks faster in some scenarios, but not in all. Analysis was limited to discrete event simulations and quantitative and statistical analysis of the results showing how long it takes to accomplish different mission scenarios. The likelihood of occurrence of each scenario is outside the scope of this paper, but should be examined by the program office. The authors recommend conducting a future experiment using active duty Marines in order to refine and validate the model.

The use of XRP systems may be found to only be beneficial in scenarios where the distance flown by the aircraft is more or less than a particular value. If the mission scenario is centered around delivering multiple sorties of full aircraft loads of cargo, such as in a force buildup or disaster relief effort, the size and weight of the XRP itself will reduce the amount of cargo each aircraft can carry. The XRP may be beneficial, depending on the speed of the aircraft, the distance flown, and the amount of time it takes to load and unload. We recommend that a statistical analysis be performed to investigate the values of these variables that result in a benefit from using the XRP instead of working parties or MHE.

A full Failure Modes, Effects, and Criticality Analysis is recommended in order to better define the logistics and maintenance burden of fielding a system such as the XRP. A logistics AoA would help determine if a pure organic maintenance construct is optimal, or if CLS should be considered for depot-level maintenance actions.

A subsequent study is recommended to investigate other potential benefits or drawbacks that may be realized from the use of an unmanned autonomous or semi-autonomous system. There may be a reduction in risk to Marines operating in non-permissive environments. Such potential benefits are not reflected in the analysis presented in this paper.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX A: REQUIREMENTS FOR THE XRP

Table 16 displays requirements derived directly from the RIF Critical Design Review (CDR) for the XRP system. It is assumed that Stratom composed the requirements with the support of Marine Corps Systems Command. The requirements do not appear to have gone through a formal review. Some requirements are ambiguous, incomplete and poorly written.

Table 16. XRP Requirements

Req #	Requirement
1	Frame needs to be able to withstand the G-force in the aircraft.
2	Frame needs to be strong enough to handle driving forces and interactions between obstacles.
3	Needs to be wide and tall enough to fit the appropriate components inside.
4	Needs to be light enough to reduce overall vehicle weight.
5	Frame size is designed for MV-22 and CH-53 aircrafts. 60 inch max width. 60 inch max height.
6	Frame size is designed to hold: standard metal and wooden pallets
7	All frame components can be accessed from above using remove-able top plate panels.
8	Axles can be removed and replaced if damaged.
9	Engine oil can be easily drained.
10	Top plate can be swapped for new configuration.
11	The XRP SHALL contain a power system with an output of 28 Volts.
12	The XRP input power system SHALL be fused.
13	The XRP SHALL be capable of supplying greater than or equal to 40 Amps of current at unregulated 28 [V].
14	The XRP SHALL regulate the main power source as necessary for all electronic components.
15	The XRP power system SHALL be capable of controlling power to individual electrical subsystem.
16	The XRP power system SHALL provide fuses for all regulated power outputs.
17	The XRP power system SHALL be capable of powering on without external power supply.
18	The XRP SHALL include a standard NATO slave plug.

Req #	Requirement
19	The XRP SHALL include a method to disconnect all electrical components from energy storage.
20	The XRP power system SHALL utilize the vehicle frame as the primary ground.
21	Diesel engine chosen to provide mechanical power
22	The XRP will have a total loaded weight under 4907 pounds. The vehicle will weigh less than 2150 pounds and be able to carry 2756 pounds.
23	XRP must be able to tow a mortar
24	Vehicle width must be less than 60 inches to load into an MV-22.
25	Desire to fit two XRP’s into an MV-22 and 3 XRP’s into a CH-53.
26	XRP cannot collide with floor, walls, or ceiling of MV-22
27	XRP has a Threshold of 1.25 m/s and Objective of 4.47 m/s (carrying 2700 pounds)
28	XRP must be able to carry 2700pounds
29	XRP shall meet 1610 m Mission distance
30	XRP shall meet longitudinal grade of 60%
31	XRP shall not weight more that 2200 (pounds)
32	XRP shall withstand a side slope angle of 20% threshold 40% objective
33	XRP shall meet Top plate Angle of 4 degrees Threshold
34	The XRP should be capable of operating at night
35	The XRP SHALL have a teleoperation mode used for direct control of the XRP vehicle. Note: Direct control corresponds to full vehicle control consisting of, but not limited to turning, forward velocity, height, braking.
36	The XRP SHALL be capable of controlling the top plate of the vehicle to within 0.5 [in] of desired height.
37	The XRP SHOULD be capable of auto unload operations, that do not require any operator command/control input.
38	The XRP Human Interface SHALL provide the operator with vehicle status. Note: Status includes but is not limited to: vehicle and sensor health, sensor information, context information, etc.
39	The XRP Human Interface SHALL directly inform the operator of any vehicle errors. Note: Directly refers to viewing precedence, so that other operations would not hide/minimize indication.
40	The XRP SHALL have electronic stop capabilities. Note: Electronic stop is defined as an electrical disconnect between motors/pumps/devices that prevents the vehicle from movement.
41	The XRP SHALL have at least one electronic stop button/switch. Note: Electronic stop is defined as an electrical disconnect between motors/pumps/ devices that prevents the vehicle from movement.

Req #	Requirement
42	The XRP SHALL automatically stop in the event of a critical system failure. Note: Critical system failure has not been defined. But will be listed in Test Case/Procedure Document TP-TBD-TBD.
43	The XRP SHALL automatically apply parking brakes in the event of a power disconnect/loss.
44	The XRP SHALL electronically stop in the event of Human Interface communication loss. Note: Electronic stop (caused by communication loss) will not occur in autonomous modes, such as waypoint.
45	The XRP SHALL electronically stop in the event of communication loss with external electronic stop device.
46	The XRP remote electronic stop device SHALL support operation up to 300 [m] Line of Sight.
47	The XRP SHALL provide external vehicle status/state indication to the operator. Note: Indication can be either visual or audible.
48	The XRP computer resources SHALL provide data storage to store greater than or equal to 24 [hrs] of critical system data. Note: Critical system data consists of, but is not limited to: E-Stops, failures, errors, etc.
49	The XRP computer resources SHALL provide data storage to store greater than or equal to 30 [s] of uncompressed system data. Note: Uncompressed system data consists of, but is not limited to: Sensor data, images, control messages, etc.
50	Long term data storage will utilize non-volatile memory with at least 32GB of storage available. Storage requirement is dominated by compressed video size 600kbps H.264 video (2 streams) requires ~12.5GB for 24 hours 32GB is more than enough for 24 hours, and is readily available in multiple form factors
51	Short term data storage will utilize volatile memory, and can be moved to non-volatile memory upon triggering events (OCU input, critical system failures, emergency stop events, etc.) Imagery - ~315Mbps Dense 3D - ~140Mbps Other data - ~100Mbps Total = 555Mbps 55 MB/s, ~1.6GB for 24 hours Need 4GB of RAM available on the data logger computer 2GB for operating system 2GB for RAM disk storage
52	The XRP SHALL have wireless communication capabilities that operate in the S or C ISM Frequency Band.
53	The XRP SHALL have a wireless communication distance of at least 1610 [m] non-obstructed line of sight.

Req #	Requirement
54	The XRP communication system SHALL NOT have an interrupted link connection during the entirety of the unpalletization mission. Note: Unpalletization Mission consists of; 1) Navigating from Cargo Loading Station onto Aircraft deck for lock down. 2) Navigating off aircraft to unload zone. 3) Self-unloading palletized cargo. 4) Navigating back to aircraft deck for lock down. 5) Navigating back to Cargo Loading Station
55	The XRP communication system SHALL NOT occupy the same frequency as external safety equipment.
56	The XRP communication system SHALL be capable of continuous throughput of at least 5 Mbps.
57	The XRP communication system SHALL have an Ethernet interface to the onboard vehicle network.
58	The XRP communication antennas SHALL NOT interfere with loading or unloading of material.
59	The XRP communication antennas SHALL be installed such that communications are not lost due to vehicle orientation.
60	The XRP communication antennas SHALL be installed such that communications are not lost due to loaded operational cargo.
61	(O)The XRP communication system SHOULD be capable of transmitting video feed with a transmission data rate of greater than or equal to 1 [Mbps].
62	The XRP SHALL have a teleoperation mode used for direct control of the XRP vehicle. Note: Direct control corresponds to full vehicle control consisting of, but not limited to turning, forward velocity, height, braking.
63	The XRP SHALL have an assisted teleoperation mode that utilizes collision stopping algorithms to halt the vehicle when an undesired obstacle collision is detected.
64	The XRP SHALL contain a Waypoint Follow mode that utilizes GPS information to navigate the vehicle without interaction from a human operator. Note: GPS signal must be obtained for waypoint follow mode to operate correctly.
65	The XRP SHALL be capable of sensing orientation, relative to the world environment.
66	The XRP SHOULD be capable of reporting current vehicle global location with a CEP accuracy of less than 10 [m]. Note: Accuracy is defined in an open field environment.
67	The XRP SHOULD be capable of reporting current vehicle global location with a CEP accuracy of less than 5 [m]. Note: Accuracy is defined in an open field environment.
68	The XRP SHALL be capable of imaging the environment in dynamic lighting conditions.

Req #	Requirement
69	The XRP Human Interface SHALL contain an Assisted Teleoperation mode that is used to control the XRP vehicle with assisted input. Note: Assisted input is defined as: Utilizing sensor information and behaviors to assist in vehicle speed/orientation control.
70	The XRP Human Interface SHOULD contain vehicle video stream(s) for remote operations.
71	The XRP SHALL have an assisted teleoperation mode that utilizes collision stopping algorithms to halt the vehicle when an undesired obstacle collision is detected.
72	The XRP SHALL be capable of assisted ramp alignment (to prevent navigating off of aircraft ramp) during unload operations.
73	The XRP SHALL be capable of assisted ramp alignment (to prevent navigating off of aircraft ramp) during load operations.
74	The XRP SHOULD be capable of auto unload operations, that do not require any operator command/control input.
76	The XRP SHALL be capable of detecting the aircraft ramp used for load/ unload operations
77	The XRP SHALL be capable of detecting large positive obstacles that include, but are not limited to: humans, walls, boulders, etc. Note: Positive Obstacles consist of obstacles that protrude from navigating surface.
78	The XRP SHALL be capable of detecting internal aircraft walls.
79	The XRP SHOULD be capable of detecting the aircraft ramp used for load/ unload in night operations.
80	The XRP SHOULD be capable of detecting large obstacles during night operations. Note: Large obstacles include, but are not limited to: humans, walls, boulders, etc.
81	The XRP SHALL be capable of preventing collisions with the transportation aircraft (including aircraft ramp and ramp accessories) during load operations.
82	The XRP SHALL be capable of preventing collisions with the transportation aircraft (including aircraft ramp and ramp accessories) during unload operations.
83	The XRP SHALL be capable of detecting large positive obstacles that include, but are not limited to: humans, walls, boulders, etc. Note: Positive Obstacles consist of obstacles that protrude from navigating surface.
84	The XRP SHALL be capable of detecting internal aircraft walls.
85	The XRP SHOULD be capable of detecting large obstacles during night operations. Note: Large obstacles include, but are not limited to: humans, walls, boulders, etc.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX B: RECOMMENDED CORRECTIONS TO DERIVED REQUIREMENTS

Table 17 displays the recommended corrections to the poorly written requirements identified during the requirements review. The recommended requirements map to the original requirement number in Appendix A.

Table 17. Recommended Corrections to Derived Requirements

Req #	Poorly Written Requirement	Corrected Requirement	Reason
1	Frame needs to be able to withstand the G-force in the aircraft.	The Frame shall withstand the G-force in the aircraft.	Never use the words “needs to be” in writing requirements to avoid ambiguity
7	All frame components can be accessed from above using remove-able top plate panels.	All components within the XRP shall be accessible above the XRP frame	Mixing specific design within a requirement is unacceptable because there are other options available to meet requirement
9	Engine oil can be easily drained.	The XRP’s engine oil change shall be accomplished by unit-level maintainers. It shall take 30 minutes or less.	Requirement is ambiguous and unclear
11	The XRP SHALL contain a power system with an output of 28 Volts.	The XRP shall contain a power system to power all components aboard	Mixing specific design within a requirement is unacceptable because there are other options available to meet requirement
12	The XRP input power system SHALL be fused.	The XRP input power system shall have safety features that protect against power surges	Mixing specific design within a requirement is unacceptable because there are other options

Req #	Poorly Written Requirement	Corrected Requirement	Reason
			available to meet requirement
13	The XRP SHALL be capable of supplying greater than or equal to 40 Amps of current at unregulated 28 [V].	The XRP shall have a steady power system for all electrical loads	Mixing specific design within a requirement is unacceptable because there are other options available to meet requirement
16	The XRP power system SHALL provide fuses for all regulated power outputs.	The XRP power system shall have safety components for all regulated power outputs.	Mixing specific design within a requirement is unacceptable because there are other options available to meet requirement
21	Diesel engine chosen to provide mechanical power	The XRP engine shall provide mechanical power to enable the XRP to move at the required speeds and under the required loads listed in other requirements.	Mixing specific design within a requirement is unacceptable because there are other options available to meet requirement
31	XRP shall not weigh more that 2200 (lb)	XRP shall weigh 2200 lb or less	Never use the words “SHALL NOT” in writing requirements to avoid ambiguity
34	The XRP should be capable of operating at night	The XRP shall be capable to be operated at night	Never use the word “SHOULD” in writing requirements to avoid ambiguity.
37	The XRP SHOULD be capable of auto unload operations, that do not require any operator command/control input.	The XRP shall be capable of auto unload operations, that do not require any operator command/control input.	Never use the word “SHOULD” in writing requirements to avoid ambiguity.

Req #	Poorly Written Requirement	Corrected Requirement	Reason
54	The XRP communication system SHALL NOT have an interrupted link connection during the entirety of the unpalletization mission. Note: Unpalletization Mission consists of; 1) Navigating from Cargo Loading Station onto Aircraft deck for lock down. 2) Navigating off aircraft to unload zone. 3) Self-unloading palletized cargo. 4) Navigating back to aircraft deck for lock down. 5) Navigating back to Cargo Loading Station	The XRP communication system shall have an un-interrupted link connection during duration of the unpalletization mission. Note: Unpalletization Mission consists of; 1) Navigating from Cargo Loading Station onto Aircraft deck for lock down. 2) Navigating off aircraft to unload zone. 3) Self-unloading palletized cargo. 4) Navigating back to aircraft deck for lock down. 5) Navigating back to Cargo Loading Station	Never use the words “SHALL NOT” in writing requirements to avoid ambiguity.
55	The XRP communication system SHALL NOT occupy the same frequency as external safety equipment.	The XRP communication system shall occupy a different frequency from external safety equipment.	Never use the words “SHALL NOT” in writing requirements to avoid ambiguity
58	The XRP communication antennas SHALL NOT interfere with loading or unloading of material.	The XRP communication antennas shall remain free and clear during loading and unloading of material.	Never use the words “SHALL NOT” in writing requirements to avoid ambiguity.
66	The XRP SHOULD be capable of reporting current vehicle global location with a CEP accuracy of less than 10 [m]. Note: Accuracy is defined in an open field environment.	The XRP shall be capable of reporting current vehicle global location with a CEP accuracy of 10 m (T) and 5 m (O)	Never use the word “SHOULD” in writing requirements to avoid ambiguity. These two requirement can be combined into an objective-threshold requirement.
67	The XRP SHOULD be capable of reporting current vehicle global location with a CEP accuracy of less than 5 [m]. Note: Accuracy is defined in an open field		

Req #	Poorly Written Requirement	Corrected Requirement	Reason
	environment.		
70	The XRP Human Interface SHOULD contain vehicle video stream(s) for remote operations.	The XRP Human Interface SHALL contain vehicle video stream(s) for remote operations.	Never use the word “SHOULD” in writing requirements to avoid ambiguity.
74	The XRP SHOULD be capable of auto unload operations, that do not require any operator command/control input.	The XRP SHALL be capable of auto unload operations, that do not require any operator command/control input.	Never use the word “SHOULD” in writing requirements to avoid ambiguity.
79	The XRP SHOULD be capable of detecting the aircraft ramp used for load/ unload in night operations.	The XRP SHALL be capable of detecting the aircraft ramp used for load/unload in night operations.	Never use the word “SHOULD” in writing requirements to avoid ambiguity.
80	The XRP SHOULD be capable of detecting large obstacles during day operations. Note: Large obstacles include, but are not limited to: humans, walls, boulders, etc.	The XRP SHALL be capable of detecting large obstacles during day operations. Note: Large obstacles include, but are not limited to: humans, walls, boulders, etc.	Never use the word “SHOULD” in writing requirements to avoid ambiguity.
85	The XRP SHOULD be capable of detecting large obstacles during night operations. Note: Large obstacles include, but are not limited to: humans, walls, boulders, etc.	The XRP SHALL be capable of detecting large obstacles during night operations. Note: Large obstacles include, but are not limited to: humans, walls, boulders, etc.	Never use the word “SHOULD” in writing requirements to avoid ambiguity.

APPENDIX C: MODELING HISTOGRAMS

Figures 24 and 25 show the time predicted by the model to load and unload MV-22 and CH-53 aircraft using working parties, material handling equipment and XRPs. A total of 100 individual runs were completed for each variation of the model.

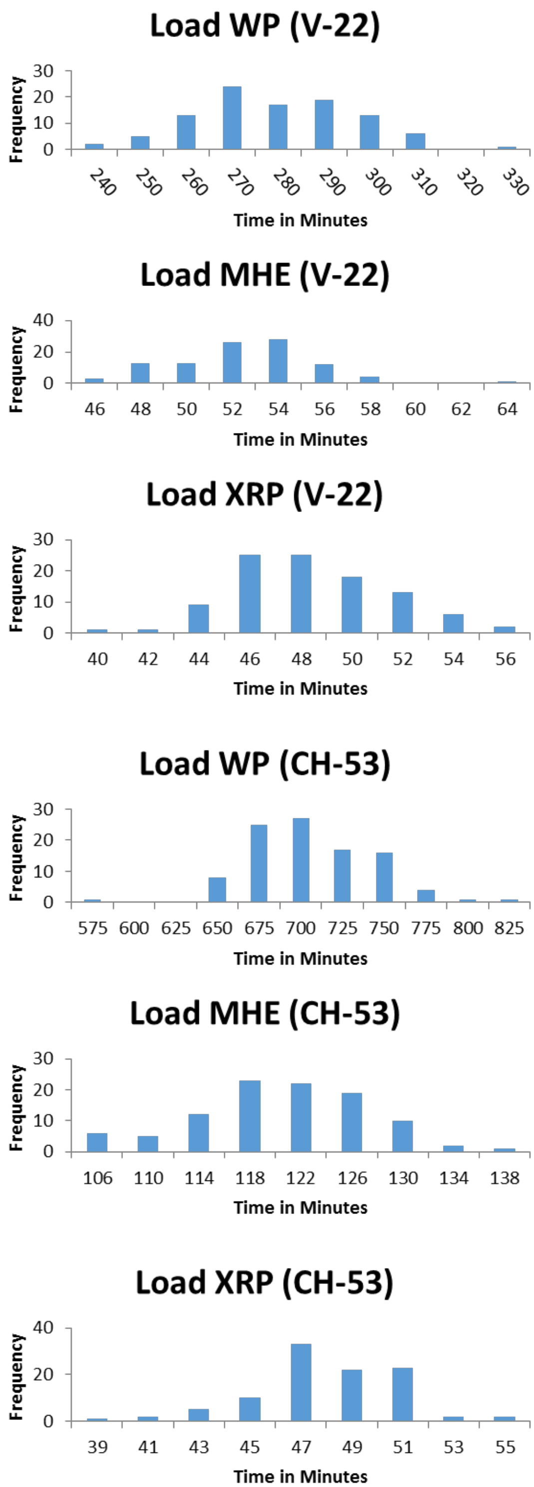

Figure 24. Load Results (100 Runs per Scenario)

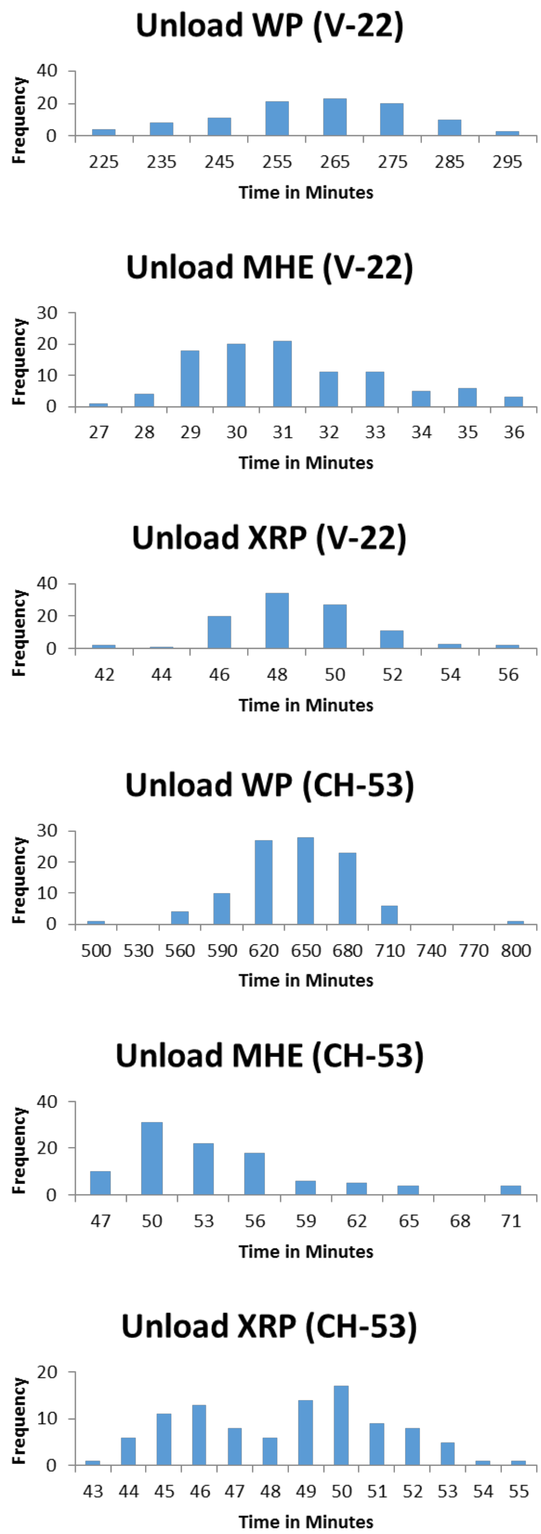

Figure 25. Unload Results (100 Runs per Scenario)

Due to the bimodal nature of the model results for unloading the CH-53 using the XRP, the number of runs was increased to 600. Results from these runs are shown in Figure 26, which removes the bimodal nature of the data with the increased number of runs.

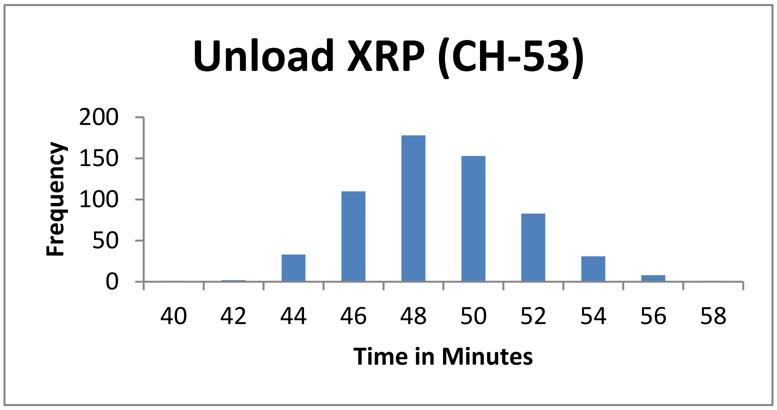

Figure 26. Unload XRP (600 Runs)

APPENDIX D: EXTENDSIM MODEL

Figure 27 through Figure 35 display the ExtendSim model that was created for the variants that were modeled for loading and unloading cargo using the three different methods onto the two aircraft.

Load Model:

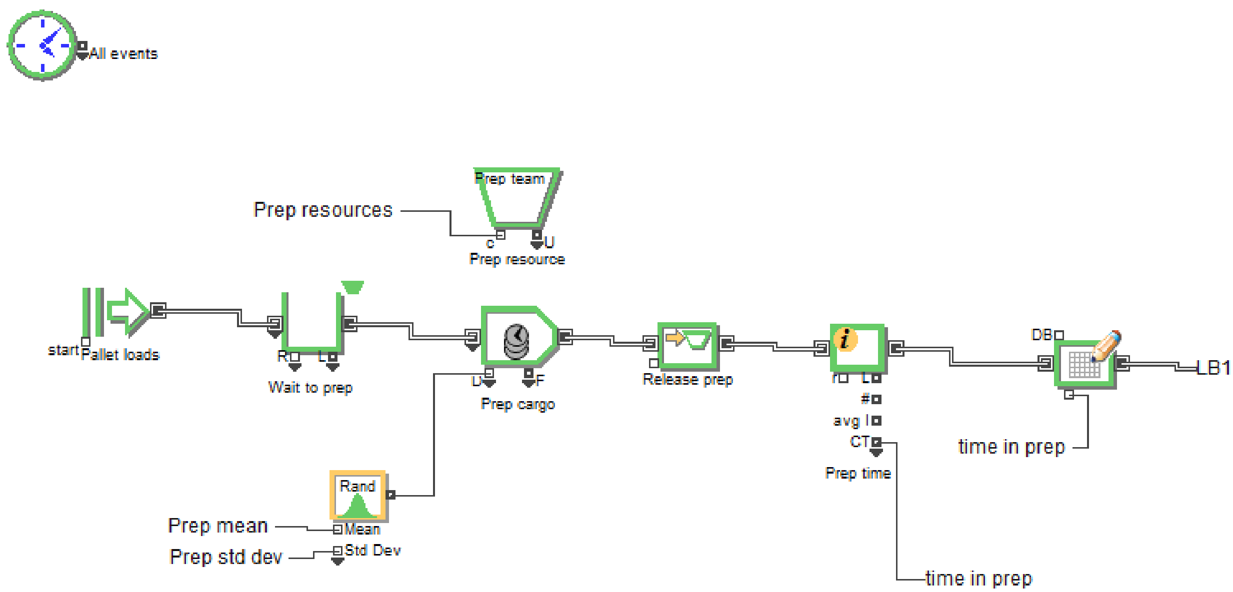

Figure 27. Part 1: Prepare Cargo

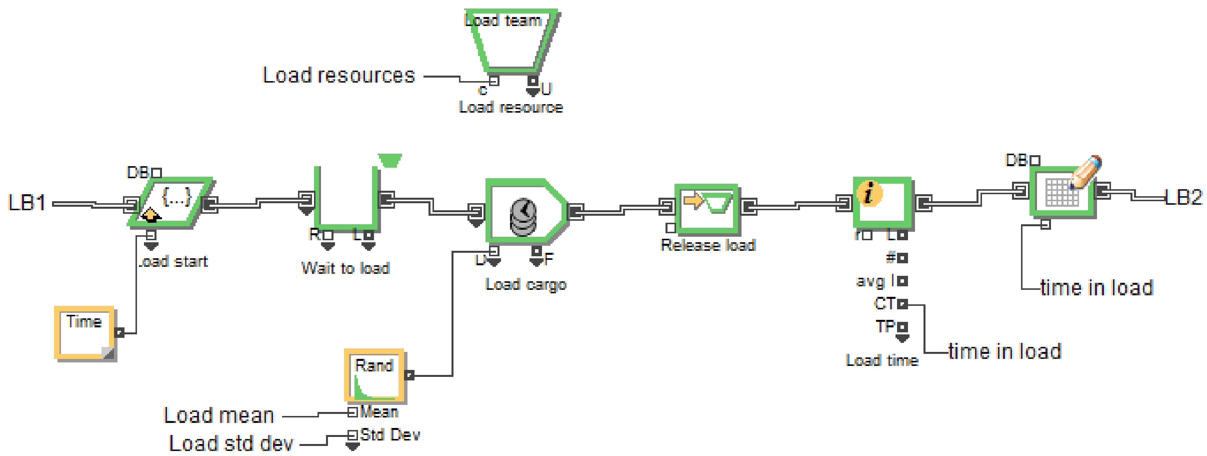

Figure 28. Part 2: Load Cargo

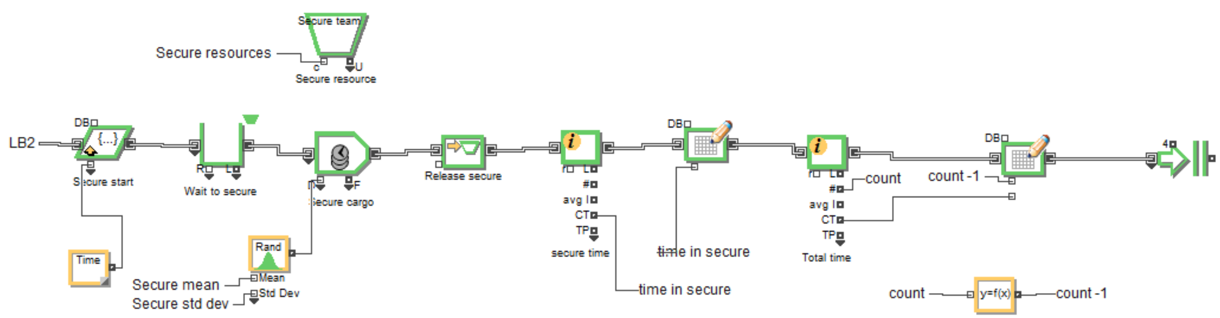

Figure 29. Part 3: Secure Cargo

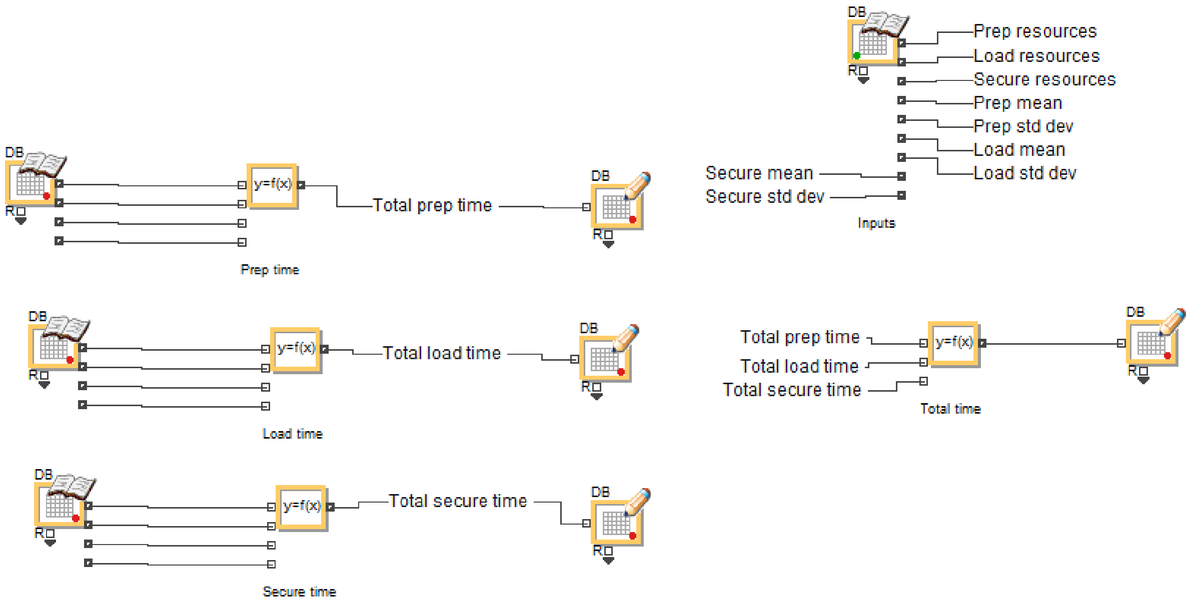

Figure 30. Database Management

Unload Model:

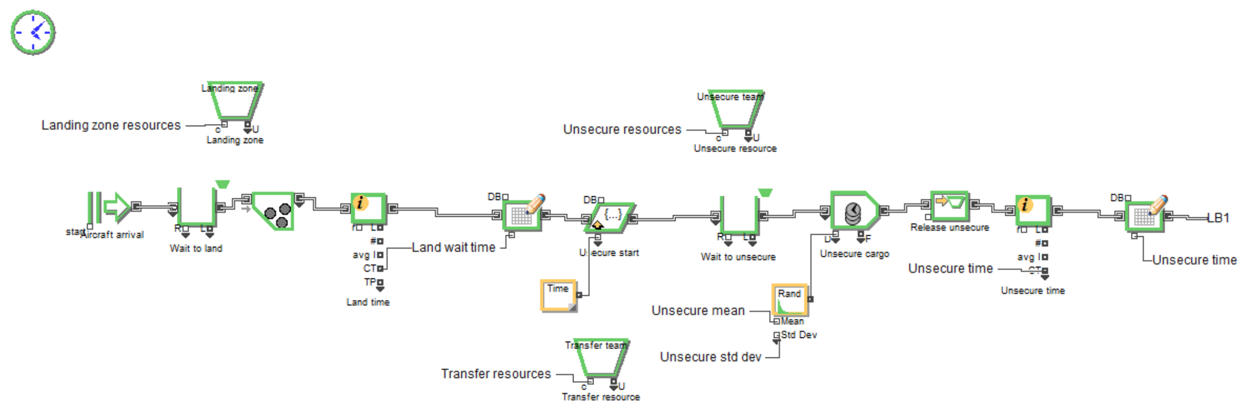

Figure 31. Part1: Landing and Unsecure Cargo

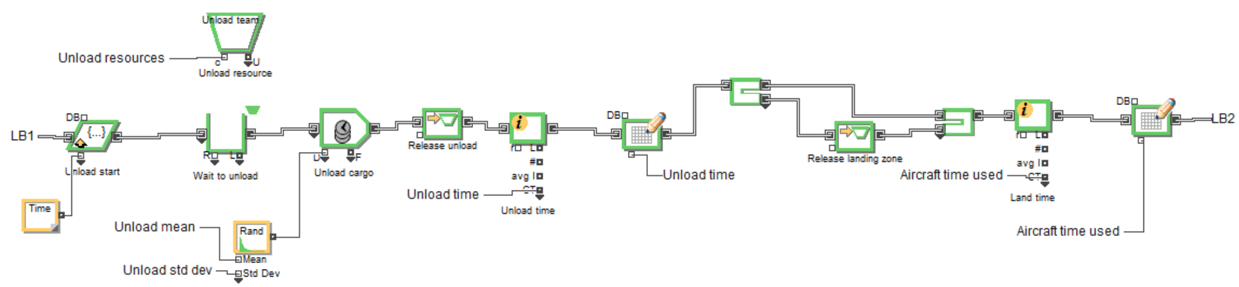

Figure 32. Part 2: Unload Cargo

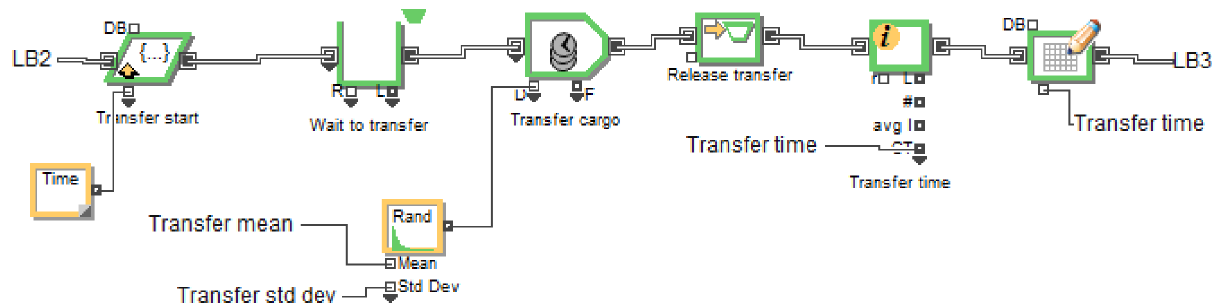

Figure 33. Part 3: Transfer Cargo

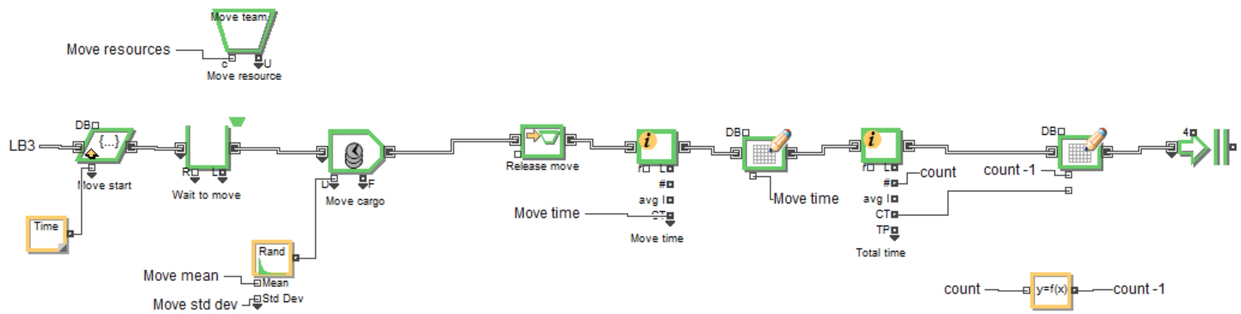

Figure 34. Part 4: Move Cargo

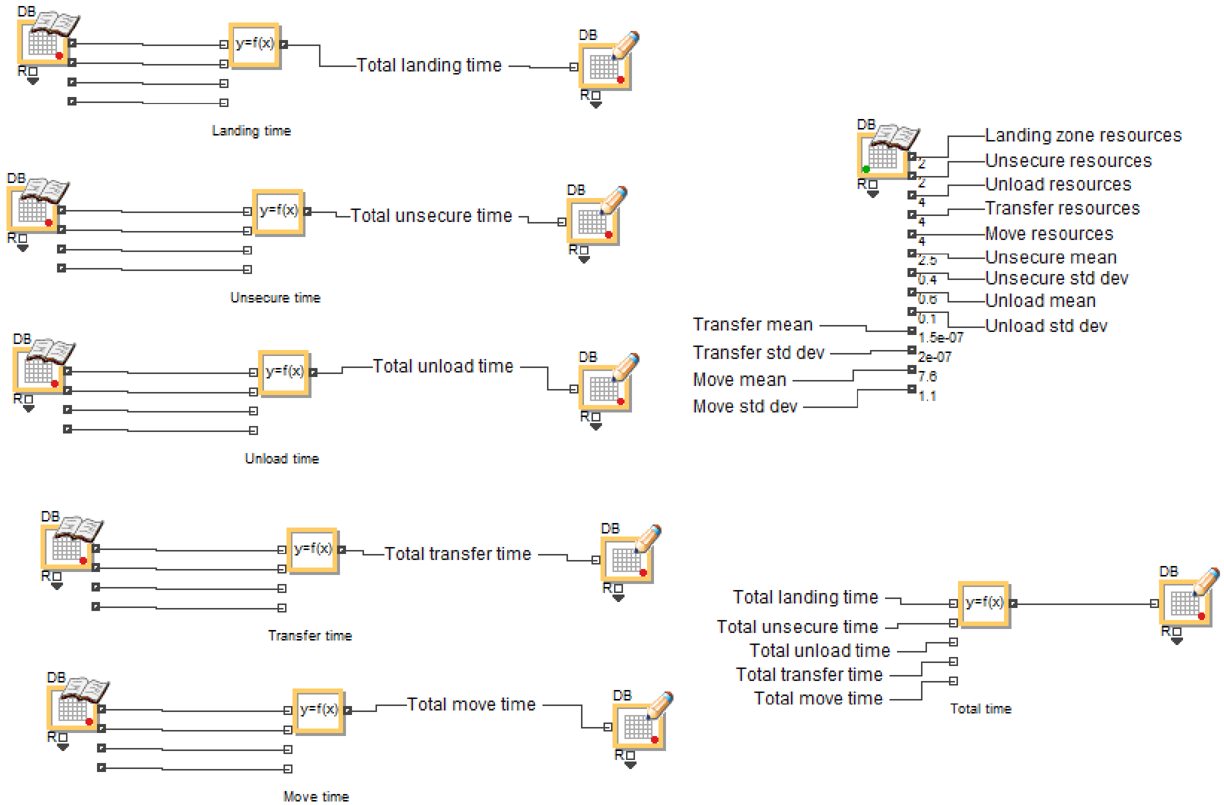

Figure 35. Part 5: Database Management

BIBLIOGRAPHY

AliExpress. 2016. "AliExpress." Accessed November 11, 2016. https://www.aliexpress.com/item/HB150-fuel-pipe-for-engine-1100-part-number-195-07900A/32722699258.html?spm=2114.40010508.4.97.DoTEKu.

Anderson, Tim. 2015. *Cost Estimating Relationships II.* Naval Postgraduate School, Monterey, CA.

Bahill, A. T., and B Gissing. 1998. "Re-evaluating Systems engineering concepts using systems thinking." *IEEE Transactions on Systems, Man and Cybernetics Part C: Applications and Reviews 28* 516–727.

Blanchard, Benjamind S., and Wolter J. Fabrycky. 2011. *Systems Engineering and Analysis,* 5th ed. Upper Saddle River: Prentice Hall.

Bureau of Labor Statistics. 2016. *Occupational Employment Statistics.* March 30. http://www.bls.gov/oes/current/oes131151.htm.

Computer Hope. 2016. "Computer Hope." http://www.computerhope.com/issues/ch000985.htm.

Defense Acquisition University. 2016a. *Glossary of Defense Acquisition Cost and Terms.* Accessed October 20, 2016. https://dap.dau.mil/glossary/Pages/1471.aspx.

———. 2016b. *Acquipedia.* May 11. Accessed October 21, 2016. https://dap.dau.mil/acquipedia/Pages/ArticleDetails.aspx?aid=a7706905-415f-496f-acd7-7cc034cfa8e1.

———. 2016c. *Defense Acquisition Guidebook Operations and Support Phase.* Accessed November 03, 2016. https://acc.dau.mil/CommunityBrowser.aspx?id=638314.

———. 2016d. *Defense Acquisition Guidebook.* Accessed November 7. https://acc.dau.mil/CommunityBrowser.aspx?id=489746#5.1.1.

———. 2016e. *Defense Acquisition GuideBook.* Accessed November 11. https://acc.dau.mil/CommunityBrowser.aspx?id=488332#3.1.3.4.

Defense Innovation Market Place. 2016. "Rapid Innovation Fund." August. Accessed August 6. http://www.defenseinnovationmarketplace.mil/rif.html.

Defense Travel Management Office. 2016. "Maximum Per Diem Rates in the Continental United States." September 28. http://www.defensetravel.dod.mil/pdcgi/pd-rates/cpdratesx4.cgi.

Defense Update. 2016. “SMSS Squad Mission Support System from Lockheed Martin.” Accessed October 20, 2016. http://defense-update.com/products/s/smss.htm.

Department of Defense. 2012. *Department of Defense Design Criteria Standard – Human Engineering MIL-STD-1472G.* Washington, DC: Department of Defense.

Diesel Specialist. 2016a. *Diesel Specialist.* Accessed November 11. http://www.dieselpartsdirect.com/KURB10151280.

———. 2016b. *Diesel Specialist.* Accessed November 11. http://www.dieselpartsdirect.com/KU1G82097010.

———. 2016c. *Diesel Specialist.* Accessed November 11. http://www.dieselpartsdirect.com/KU1916711080.

Enterprise. 2016. “Choose a vehicle class.” October 23. Accessed October 23, 2016. https://www.enterprise.com/en/reserve.html#cars.

Eskew, H. L., and K. S. Lawler. Spring 1994. “Correct and Incorrect Error Specifications in Statistical Cost Models.” *Journal of Cost Analysis* 107.

ExtendSim. 2016. *Overview of ExtendSim.* Accessed August 22, 2016. https://www.extendsim.com/prods_overview.html.

General Dynamics. 2016. *EFFS: Expeditionary Fires Support System.* Accessed July 10 . http://www.gd-ots.com/efss.html.

General Dynamics Ordnance and Tactical Systems. 2008. *Expeditionary Fire Support System.* Manufacturer’s Brochure, St Petersburg: General Dynamics Ordnance and Tactical Systems.

GoWarn. 2015. “Go Warn.” https://www.gowarn.com/prodDetail.aspx?partNo=war87800&utm_source=google&utm_medium=cpc&utm_campaign=shopping&emlprox=out&ppcfon=1&gp=1&gclid=CjwKEAiA6rrBBRDsrLGM4uTPkWASJADnWZQ4BPHb3Tu4-NMC9h8PMW-LE_exZnAOcYkFrJJIkBJOBBoCh43w_wcB.

Greenberg, Andy. 2011. *BigDog Goes To War.* May 04. http://www.forbes.com/forbes/2011/0523/technology-boston-dynamics-youtube-bigdog-goes-war.html.

Hayter, Anthony. 2006. *Probability and Statistics For Engineers and Scientists 3rd Edition.* Boston: Brooks/Cole.

Headquarters, Department of the Army. 1997. *Transportation Reference Data, Field Manual No. 55-15.* Washington, DC: Department of the Army.

Hstar Technologies. 2016. “Commercial and Military Freight & Material Handling.” Accessed November 7, 2016. http://www.hstartech.com/index.php/dman.html.

Kubota Farm & Industrial Machinery Service. 2012. *Workshop Manual Diesel Engine.* Sakai, Japan: Kubota Corporation.

Kumar Bros USA. 2012. “Overhual Kit Suitable For Kubota.” http://www.kumarbrosusa.com/kubota/kubota-overhaul-kits.html.

Loopnet. 2016. *Boulder CO Market Trends.* Accessed November 8, 2016. http://www.loopnet.com/Boulder_Colorado_Market-Trends.

Loughran, Maire. 2016. *The Costs of Research and Development (R&D).* Accessed October 19, 2016. http://www.dummies.com/business/accounting/the-costs-of-research-and-development-rd/.

Madison Tractor Company. 2014. *Madison Tractor Company.* Accessed November 04, 2016. https://www.madisontractor.com/tractor-parts/cooling-system/radiator-hoses/kubota.html.

Marine Corps Systems Command. 2016. *Systems Engineering, Interoperability, Architectures & Technology (SIAT).* July 10. http://www.marcorsyscom.marines.mil/Professional-Staff/SIAT/.

McMahon, Karen. 2010. “New Gator Utility Vehicles from John Deere.” http://farmindustrynews.com/atvuv/new-gator-utility-vehicles-john-deere.

MCTSSA. 2016. *Marine Corps Tactical Systems Support Activity*. July 10. http://www.marcorsyscom.marines.mil/Professional-Staff/DC-SIAT/MCTSSA/.

militarymashup.com. 2016. Accessed May 13, 2016. http://militarymashup.com/mmu_get_jpeg.php?1c356dc79cfe1165c86c60239e049325f.

Mizokami, Kyle . 2016. “One Chart that Explains How the U.S. Marines Fight.” April 13. Accessed April 18, 2016. http://www.popularmechanics.com/military/weapons/a20388/how-the-us-marines-fight/.

Naval Air Systems Command. 2015. *Cargo Handling Manual V-22 Tiltrotor (A1-V22AB-CLG-000).* Patuxent River, MD: Naval Air Systems Command.

Naval Center for Cost Analysis. 2016. *NCCA Inflation Indices and Joint Inflation Calculator*. February. Accessed October 22, 2016. https://www.ncca.navy.mil/tools/inflation.cfm.

Nielsen, Jakob. 1997. “Loaded Cost of Employee Time.” June 15. Accessed October 28, 2016. https://www.nngroup.com/articles/loaded-cost-of-employee-time/.

Office of the Assistant Secretary of Defense for Logistics & Materiel Readiness. 2015. *DOD Maintenance Fact Book.* Accessed November 03, 2016. http://www.acq.osd.mil/log/mpp/field.html.

Office of the Secretary of Defense. 2014. *Operating and Support Cost-Estimating Guide.* March. http://www.cape.osd.mil/files/OS_Guide_v9_March_2014.pdf.

OPM. 2016. *Pay & Leave, Salaries & Wages.* January. Accessed October 22, 2016. https://www.opm.gov/policy-data-oversight/pay-leave/salaries-wages/salary-tables/pdf/2016/GS.pdf.

Owen, Randy. 2016. “Government Fleet, Calculating Mechanic Staffing Requirements.” Accessed November 05, 2016. http://www.government-fleet.com/article/story/2009/11/calculating-mechanic-staffing-requirements/page/3.aspx.

PartsTree. 2014a. “PartsTree.” Accessed November 11, 2016. https://www.partstree.com/parts/exmark/parts/2412-42/.

———. 2014b. “PartsTree.” Accessed November 11, 2016. https://www.partstree.com/parts/exmark/parts/103-7597/.

———. 2014c. “PartsTree.” Accessed November 11, 2016. https://www.partstree.com/parts/exmark/parts/92-2379/.

Rockwell Collins. 2012. “MicroGRAM Performance Specification.” Performance Specification. Rockwell Collins, Cedar Rapids, IA.

Rouse, Margaret. 2007. “TechTarget.” Accessed May 17, 2016. http://searchsoftwarequality.techtarget.com/definition/requirements-analysis.

SBA. 2016a. *SBIR STTR.* Accessed August 18, 2016. https://www.sbir.gov/about/about-sbir#sbir-program.

———. 2016b. *Self-propelled Robotic Pallet.* Accessed October 1, 2016. https://www.sbir.gov/sbirsearch/detail/415661.

Scuba. 2016. *Scuba.* Accessed November 11, 2016. http://www.scuba.com/US/scuba-gear-67/008178/Suunto-USB-PC-Interface.html?gclid=Cj0KEQjwhvbABRDOp4rahNjh-tMBEiQA0QgTGnCqQZrAjHIJOOLIxDHqlkMnCnqMJykpVBO__D9FzqwaAnD68P8HAQ.

Southeastern Equipment & Supply. 2016. *Southeastern Equipment & Supply.* Accessed November 11, 2016. http://www.southeasternequipment.net/product-p/AD7-33-02687.htm?gclid=CNbRz9Trj9ACFRYGhgod3bcJFw.

SPAWAR Atlantic. 2016. *Warehouse Pallet Fees Reference Page.* October 14. Accessed October 15, 2016. https://wiki.spawar.navy.mil/confluence/display/SSCACOG/Warehouse+Pallet+Fees+Reference+Page.

Stratom. 2015. *eXpeditionary Robo-Pallet Systems Requirements Review (SRR).* Brief, Stratom, Boulder, CO.

Stratom. 2016. *RIF Critical Design Review (CDR)*. Stratom, Boulder, CO.

Time Inc. (UK) Ltd Technology Network. 2016. *What Digital Camera.* Accessed November 11, 2016. http://www.whatdigitalcamera.com/buying-advice/understanding-memory-cards-9083.

Tornado Parts. 2015. *Tornado Heavy Equipment Parts.* Accessed November 11, 2016. http://tornadoparts.com/11289-320-T.

U.S. Army Research Institute for the Behavioral and Social Sciences. 2010. *Soldiers' Toolbox for Developing Tactics, Techniques, and Procedures (TTP).* Arlington, VA: U.S. Army Research Institute for the Behavioral and Social Sciences.

U.S. Energy Information Administration. 2016. *Gasoline and Diesel Fuel Update* . October 11. Accessed October 15, 2016. http://www.eia.gov/petroleum/gasdiesel/.

Under Secretary of Defense (Comptroller). 2016. *Financial Management Reports.* March 09. Accessed October 22, 2016. http://comptroller.defense.gov/Financial-Management/Reports/rates2017/.

United Airlines. 2016. "United." October 22. Accessed October 22, 2016. https://www.united.com/ual/en/us/flight-search/book-a-flight/reviewflight/rev.

United States Marine Corps. 1996. *Tactics, Techniques, and Procedures for the Field Artillery Cannon Battery* (MCWP 3–1.6.23). Washington, DC: U.S. Government Printing Office.

———. 2000. *Contractor Logistics Support for Ground Equipment, Ground Weapon Systems, Munitions, and Information Systems* (MCO 4200.33). Washington, D.C.: U.S. Government Printing Office.

———. 2001. *Aviation Ground Support.* Quantico: Commanding General, Marine Corps Combat Development Command, Doctrine.

———. 2013. *Operator/Crew Technical Manual for Mortar, 120MM, Rifled, Towed, M327* (TM 11166A-OR). Quantico, VA: Marine Corps Systems Command.

———. 2014a. *Expeditionary Force 21.* March 4.

———. 2014b. *Ground Equipment Maintenance Program* (MCO 4790.25). Washington, D.C.: Department of the Navy.

UsShip. 2016. *Shipping CalculatorShipping Calculator.* Accessed October 14, 2016. https://www.uship.com/shipping-calculator.aspx.

Wade, Norman M. 2016. *Marine Corps Planning Process (MCPP).* Accessed May 20, 2016. https://www.thelightningpress.com/marine-corps-planning-process-mcpp/.

Walmart. 2016a. "Walmart." Accessed November 11, 2016. https://www.walmart.com/browse/auto-tires/motor-oil/91083_1104294_1072084.

———. 2016b. "Walmart." Accessed November 11, 2016. https://www.walmart.com/browse/auto-tires/oil-filters/91083_1074765_8697188_1044301.

Warn. 2016. "Warn." *Warn.* 10 13. Accessed 11 18, 2016. https://www.warn.com/manuals/assets/pdf/15119xx_7yyearelectrical_13Oct2016.pdf.

Weingartz Supply. 2015. Accessed November 11, 2016. https://weingartz.com/PD/3576538/toro-track-rubber-121-1021.

Worley, Duane Robert. 2006. *Shaping U.S. Military Forces: Revolution or Relevance in a Post-Cold War World.* Westport: Praeger Security International.

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California